mpatrol

A library for controlling and tracing dynamic memory allocations
Edition 2.5 for mpatrol version 1.4.0
21st February, 2001

Graeme S. Roy

Table of Contents

mpatrol

This document describes mpatrol, a library for controlling and tracing dynamic memory allocations.

This is edition 2.5 of the mpatrol manual for version 1.4.0, 21st February, 2001.

Foreword

I first started writing this library a few years ago when the company I work for sent me out to a customer who had reported a memory leak, which he expected was coming from the code generated by our C++ compiler. A few years on and the library has changed dramatically from its first beginnings, but I thought I'd release it publicly in case anyone else found it useful.

When writing the library, I placed more emphasis on the quantity and quality of information about allocated memory rather than the speed and efficiency of allocating the actual memory. This means that the library will use dramatically more memory than normal dynamic memory allocation libraries and can slow down to a crawl depending on which options you use. However, the end results are likely to be accurate and reliable, and in most cases the library will run quite happily at a sane speed.

The mpatrol library is by no means the only library of its kind. Solaris has no less that 6 different malloc libraries, and there are plenty available as freeware or as commercial products. Try to keep in mind that mpatrol comes with absolutely no warranty and so if it doesn't work for you and you need a fast solution, try some of the other libraries or products available. I have listed some of the most popular at the end of this manual (see Appendix J [Related software], page 181).

This manual is arranged so that complete reference material on the mpatrol library can be found in the appendices, while introductory and background material can be found in the preceding chapters and sections. For readers who wish to delve right in and use the library, the Installation (see Chapter 3 [Installation], page 13) and Examples (see Chapter 12 [Examples], page 75) chapters should be enough to get started in combination with the quick reference card. Otherwise, this manual should be read from beginning to end in order to get the most out of the software it describes. Note that all of the output shown from the examples was produced on 32-bit environments, although mpatrol can be built to support 64-bit environments as well.

Due to their very nature, problems with dynamic memory allocations are notoriously difficult to reproduce and debug, and this is likely to be the case if you find a bug in the mpatrol library as it might be extremely hard to reproduce on another system. Details on how to report bugs are given elsewhere in this document (see Appendix H [Notes], page 163), but it would be very useful if you could try to provide as much information as possible when reporting a problem, and that includes having a look in the library source code to see if it's obvious what is wrong. However, please try to read the frequently asked questions (see Appendix I [Frequently asked questions], page 171) first in case your question or problem is covered there since they are usually updated every time I receive a question about mpatrol.

The latest version of the mpatrol library and this manual can always be found at `http://www.cbmamiga.demon.co.uk/mpatrol/`, and any correspondence relating to mpatrol (bug reports, enhancement requests, compliments, etc.) should be sent to `mpatrol@cbmamiga.demon.co.uk`. I'd be very interested in hearing any success stories with using mpatrol to debug programs, since I get very little feedback apart from the occasional bug report. The mpatrol library is also registered at FreshMeat (`http://freshmeat.net/projects/mpatrol/`) and SourceForge (`http://sourceforge.net/projects/mpatrol/`) and several other software sites so you can receive notification of updates there as well. I normally only check my e-mail about once or twice a week, so don't expect an immediate response. I can also be reached at `graeme@epc.co.uk` but that is my work e-mail address. There is also a discussion group at `http://groups.yahoo.com/group/mpatrol/` where you can post mpatrol-related questions but you must first subscribe to the group before you can send mail to it.

Finally, I'd like to thank Stephan Springl (`springl@bfw-online.de`) for his help on reading debugging information from object files via the GNU BFD library, and Alexander Barton (`abarton@innotrac.com`) and Dave Gibson (`david@epc.co.uk`) for their help on writing thread-safe code. Roger Keane (`rgr@bcs-inc.com`) provided the perl code in the `mpsym` command and

also the idea for the MP_USE_ATEXIT feature macro. Boris Makushkin (oberon@antibiotic.ru) requested, helped with, and provided initial testing for the FreeBSD port.

Oh, and always remember to do final release builds without the mpatrol library as the library is much slower than normal malloc implementations and uses much more memory.

Happy debugging!

Graeme Roy, 11th October, 1999.

Edinburgh, Scotland.

1 Overview

The mpatrol library is yet another link library that attempts to diagnose run-time errors that are caused by the wrong use of dynamically allocated memory. If you don't know what the `malloc()` function or `operator new[]` do then this library is probably not for you. You have to have a certain amount of programming expertise and a knowledge of how to run a command line compiler and linker before you should attempt to use this.

Along with providing a comprehensive and configurable log of all dynamic memory operations that occurred during the lifetime of a program, the mpatrol library performs extensive checking to detect any misuse of dynamically allocated memory. All of this functionality can be integrated into existing code through the inclusion of a single header file at compile-time. On UNIX and Windows platforms (and AmigaOS when using `gcc`) this may not even be necessary as the mpatrol library can be linked with existing object files at link-time or, on some platforms, even dynamically linked with existing programs at run-time.

All logging and tracing output from the mpatrol library is sent to a separate log file in order to keep its diagnostics separate from any that the program being tested might generate. A wide variety of library settings can also be changed at run-time via an environment variable, thus removing the need to recompile or relink in order to change the library's behaviour.

A file containing a summary of the memory allocation profiling statistics for a particular program can be produced by the mpatrol library. This file can then be read by a profiling tool which will display a set of tables based upon the accumulated data. The profiling information includes summaries of all of the memory allocations listed by size and the function that allocated them and a list of memory leaks with the call stack of the allocating function. It also includes a graph of all memory allocations listed in tabular form, and an optional graph specification file for later processing by the `dot` graph visualisation package.

A file containing a concise encoded trace of all memory allocations and deallocations made by a program can also be produced by the mpatrol library. This file can then be read by a tracing tool which will decode the trace and display the events in tabular or graphical form, and also display any relevant statistics that could be calculated.

The mpatrol library has been designed with the intention of replacing calls to existing C and C++ memory allocation functions as seamlessly as possible, but in many cases that may not be possible and slight code modifications may be required. However, a preprocessor macro containing the version of the mpatrol library is provided for the purposes of conditional compilation so that release builds and debug builds can be easily automated.

2 Features

An overall list of features contained in the mpatrol library is given below. This is not intended to be exhaustive since the best way to see what the library does is to read the documentation and try it out.

- Written for 32-bit and 64-bit UNIX, AmigaOS, Windows and Netware platforms. Contains direct support for (and takes advantage of most of the features of) AIX, DG/UX, DRS/NX, DYNIX/ptx, FreeBSD, HP/UX, IRIX, Linux, LynxOS, NetBSD, OpenBSD, SINIX, Solaris, SunOS and UnixWare. Also contains target-specific code to take advantage of Intel 80x86, Motorola 680x0 and 88xx0, MIPS, HP PA/RISC, IBM RS/6000, PowerPC and SPARC processors.
- Has the ability to read symbols from executable files and shared libraries in the '`a.out`', COFF, XCOFF, ELF32, ELF64 and Windows Portable Executable file formats, and if the GNU BFD library is available then the mpatrol library can read symbols from all of the file formats that it has support for as well. Can also liase with AIX, BSD-based, HP/UX, IRIX, SVR4-based and Windows dynamic linkers in order to find out information about shared libraries.
- Can be built to allocate memory from a fixed-sized static array rather than using heap memory from the system.
- Can be built as archive, shared and/or thread-safe libraries on systems that support them, or even as one large object file. A lint library can also be built from the mpatrol library on UNIX platforms.
- A release version of the mpatrol library is provided, which has the same functional interface, but does not contain any of mpatrol's debugging, tracing or profiling features. It is intended to be used to quickly remove the mpatrol library.
- Details of memory allocations and free memory are stored internally as a tree structure for speed and also to allow the best fit allocation algorithm to be used. This also enables the library to perform intelligent resizing of memory allocations and can be used to quickly determine if an address has been allocated on the heap.
- Contains 19 replacement C dynamic memory allocation functions:

`malloc()`	ANSI	Allocates memory.
`calloc()`	ANSI	Allocates zero-filled memory.
`memalign()`	UNIX	Allocates memory with a specified alignment.
`valloc()`	UNIX	Allocates page-aligned memory.
`pvalloc()`	UNIX	Allocates a number of pages.
`alloca()`	old	Allocates temporary memory.
`strdup()`	UNIX	Duplicates a string.
`strndup()`	old	Duplicates a string with a maximum length.
`strsave()`	old	Duplicates a string.
`strnsave()`	old	Duplicates a string with a maximum length.
`strdupa()`	old	Duplicates a string.
`strndupa()`	old	Duplicates a string with a maximum length.
`realloc()`	ANSI	Resizes memory.
`reallocf()`	BSD	Resizes memory and frees on failure.
`recalloc()`	old	Resizes memory allocated by `calloc()`.
`expand()`	old	Resizes memory but does not relocate it.
`free()`	ANSI	Frees memory.
`cfree()`	old	Frees memory allocated by `calloc()`.
`dealloca()`	new	Explicitly frees temporary memory.

- Contains 5 replacement C dynamic memory extension functions:

`xmalloc()`		Allocates memory without failure.

`xcalloc()`	Allocates zero-filled memory without failure.
`xstrdup()`	Duplicates a string without failure.
`xrealloc()`	Resizes memory without failure.
`xfree()`	Frees memory.

- Contains 6 replacement C dynamic memory alternative functions:

`MP_MALLOC()`	Allocates memory without failure.
`MP_CALLOC()`	Allocates zero-filled memory without failure.
`MP_STRDUP()`	Duplicates a string without failure.
`MP_REALLOC()`	Resizes memory without failure.
`MP_FREE()`	Frees memory.
`MP_FAILURE()`	Sets the allocation failure handler.

- Contains 4 replacement C++ dynamic memory allocation operators (in both *throw* and *nothrow* forms):

`operator new`	Allocates memory.
`operator new[]`	Allocates memory for an array.
`operator delete`	Frees memory.
`operator delete[]`	Frees memory allocated by `operator new[]`.

- Contains 10 replacement C memory operation functions:

`memset()`	ANSI	Fills memory with a specific byte.
`bzero()`	UNIX	Fills memory with the zero byte.
`memccpy()`	UNIX	Copies memory up to a specific byte.
`memcpy()`	ANSI	Copies non-overlapping memory.
`memmove()`	ANSI	Copies possibly-overlapping memory.
`bcopy()`	UNIX	Copies possibly-overlapping memory.
`memcmp()`	ANSI	Compares two blocks of memory.
`bcmp()`	UNIX	Compares two blocks of memory.
`memchr()`	ANSI	Searches memory for a specific byte.
`memmem()`	UNIX	Searches memory for specific bytes.

- All of the above functions can also be defined with an additional underscore prepended to their external name in order to catch all uses of these functions in the system and third-party libraries.
- Contains support for a user-defined low-memory handler function, including a replacement for the C++ function, `set_new_handler()`.
- The C++ dynamic memory allocation operators make use of the preprocessor in order to obtain source-level information. If this causes problems then replacement operator names may be used so that the existing operators will still work.
- Contains support for user-defined prologue and epilogue callback functions, which get called before and after every memory allocation, reallocation or deallocation.
- A function is provided to return as much information as possible about a given memory allocation, and can be called at any time during program execution. A similar function is also provided for calling from within a debugger and an example command file is provided for use with `gdb`.
- A function is provided to display library settings and heap usage statistics, including peak memory usage. This information is also displayed at program termination, and can also be placed into a data structure at run-time via another function.
- The library reads any user-controllable options at run-time from an environment variable, but this does not have to be set as defaults will then be used. This prevents having to recompile anything in order to change any library settings. An option exists to display a quick-reference summary of all of the recognised options to the standard error file stream. Library settings can also be set and read from within user code after the library has been initialised by calling two internal functions.

- All diagnostics and logging are sent to a file in the current directory, but this can be overridden, including forcing the log file to be the standard output or standard error file streams. An environment variable specifying a default directory in which to place log files can also be set.
- Options exist to log details of every memory allocation, reallocation or deallocation when they occur. A function exists to log the details of any memory allocation to the mpatrol log file.
- Options exist to halt the program at a specific memory allocation, reallocation or deallocation when running the program within a debugger. These options have no effect when running the program without a debugger.
- An option exists to enable memory allocation profiling, which forces a summary of all memory allocation statistics to be written to a specified file for later use by a profiling command. The profiling file can also be written at a specified frequency. An environment variable specifying a default directory in which to place profiling output files can also be set.
- A profiling command is provided which reads a profiling output file produced by the mpatrol library and displays a set of tables based on the accumulated data. The profiling information includes summaries of all of the memory allocations listed by size and the function that allocated them and a list of memory leaks with the call stack of the allocating function. It also includes a graph of all memory allocations listed in tabular form, and an optional graph specification file for later processing by the `dot` graph visualisation package.
- An option exists to enable memory allocation tracing, which forces certain details for every memory allocation event to be written to a specified file for later use by a tracing command. The tracing file is written in a concise encoded form so as to keep the size of the file down. An environment variable specifying a default directory in which to place tracing output files can also be set.
- A tracing command is provided which reads a tracing output file produced by the mpatrol library and displays the memory allocation events in tabular or graphical form. It also displays any relevant statistics that could be calculated.
- On UNIX platforms, the `mmap()` function can optionally be used to allocate user memory instead of the `sbrk()` function, but only if the system supports it. If `mmap()` is supported then internal mpatrol library memory is normally allocated with this function in order to segregate it from user memory but this behaviour can be swapped around.
- On non-UNIX platforms where the mpatrol library overrides `malloc()` without requiring the inclusion of '`mpatrol.h`', versions of the UNIX functions `brk()` and `sbrk()` are provided for compatibility with certain libraries. These should *not* be called by user code as they have only limited functionality.
- All newly-allocated memory that is not allocated by the `calloc()` or `recalloc()` functions will be pre-filled with a non-zero value in order to catch out programs that wrongly assume that all newly-allocated memory is zeroed. This value can be modified at run-time.
- Can automatically check to see if there have been any illegal writes to bytes located just before and after every memory allocation through the use of overflow buffers. The size of such overflow buffers and the value to pre-fill them with can be modified at run-time. The checks will be performed before every memory allocation call to ensure that nothing has overwritten the overflow buffers, but a function is also provided to perform additional checks under the programmer's control and an option exists to specify a range and frequency in which checks will be performed.
- On systems that support them, watch point areas can be used instead of overflow buffers so that every read and write to memory is checked to ensure that it is not within an overflow buffer.
- Supports the '`-fcheck-memory-usage`' option of `gcc` to check all heap memory accesses in programs that were compiled with that option. Currently this only supports checking

that memory accesses do not overflow heap allocations or access free memory, rather than keeping records of individual memory accesses that GNU Checker does.

- Can automatically check to see if there have been any illegal writes to free memory blocks. The value to pre-fill free memory blocks with can be modified at run-time. The check will be performed before every memory allocation call to ensure that nothing has overwritten the free memory block, but a function is also provided to perform additional checks under the programmer's control and an option exists to specify a range in which checks will be performed.
- On systems that support memory protection, every memory allocation can optionally be allocated at least one page of memory. That way, any free memory blocks can be made read and write protected so that nothing can access free memory on the heap. An option is provided to specify whether all memory allocations should be allocated at the start or at the end of such pages, and the bytes left over within the pages become overflow buffers.
- All freed memory allocations can optionally be prevented from being returned to the free memory pool. This is useful for detecting if use is being made of freed memory just after a memory allocation has been freed. The contents of the memory allocation can either be preserved or can be pre-filled with a value in order to detect illegal writes to the freed memory allocation. In addition, only a specified number of recently-freed memory allocations can be prevented from being returned to the free memory pool. Any older freed memory allocations will then eventually be reused.
- The `alloca()`, `strdupa()` and `strndupa()` functions are implemented so that the temporary stack-based allocations that they would normally make are now temporary heap-based allocations that can be traced by mpatrol. Such allocations will be implicitly freed when the function that allocated them returns, but a function also exists to explicitly free them as well.
- Calls to memory operation functions (such as `memset()` or `memcpy()`) have their arguments checked to ensure that they do not pass null pointers or attempt to read or write memory straddling the boundary of a previously allocated memory block, although an option exists to turn such an error into a warning so that the operation can still be performed. Tracing from all such functions can also optionally be written to the log file.
- The internal data structures used by the library are kept separate from the rest of the memory allocations. On systems that support memory protection, all of these internal data structures will be write-protected in order to prevent corruption by the calling program. This feature can be overridden at run-time as it can slow the program down.
- Certain signals can be saved and restored on entry to each library function and `errno` is set to `ENOMEM` if memory cannot be allocated, except for the ANSI C++ operators which throw the `std::bad_alloc` exception instead.
- On systems that support memory protection, the library attempts to detect any illegal memory accesses and display as much information as it can obtain about the address in question and where the illegal memory access occurred.
- A call stack traceback from any function performing a memory allocation is stored if the library supports this feature on the system it is being run on. This information can then be displayed when information about a specific memory allocation is required. Many different call stack traceback implementations are provided for different platforms. A function is also provided to write the current call stack to the mpatrol log file.
- Symbol table details from executable files and shared libraries are automatically read on systems that support this feature in order to make the call stack tracebacks more meaningful. An option also exists to display a complete list of the symbols that were read by the library at program termination. A function is also provided to return symbolic information about any code address.
- Compiler-generated line number tables from any debugging sections that exist in executable files and shared libraries can also be used by the mpatrol library in order to provide more

meaningful information in call stack tracebacks. An external command is also provided to make use of a debugger to get such information if one is available.

- If the library is unable to automatically determine a program's executable filename to read symbols from then an option exists to specify the full path to the program's executable file.
- Options are provided to edit and list a source file at a specific line number when a warning or error occurs due to that source line. An external command which provides this functionality outwith the mpatrol library is included, and functions are provided to do this from within user code.
- An option exists to change the default alignment used for general-purpose memory allocations.
- Contains support for a user-defined limit to available memory which can be useful for stress-testing a program in simulated low memory conditions.
- Contains a feature to randomly fail a specific frequency of memory allocations which can be useful for stress-testing error recovery code in a program.
- An option exists to display a complete memory map of the heap at program termination. A function to do this is also available to call at any point during program execution.
- A function is provided to take a snapshot of the heap at the current point in execution. The value returned by this function can then be used to pinpoint the differences in heap allocation details between that point and a later point in the program.
- A function is provided to iterate across all of the current heap allocations and call a user-defined callback function for each one it finds.
- Functions are provided to write user-defined information directly to the mpatrol log file, as well as hexadecimal memory dumps of any memory location.
- Options exist to display all freed and unfreed memory allocations at program termination in order to detect memory leaks, as well as all free memory blocks. A separate program is also provided for locating memory leaks in unfinished log files.
- An option exists to abort the program with a failure condition if there are more than a specified number of unfreed memory allocations at program termination. This could be useful for batch testing in order to check that all tests free up most of their allocated memory.
- Functions always report if their arguments are illegal in order to pinpoint any errors, and options exist to perform rigorous checking of arguments when allocating, reallocating and freeing memory. In addition, checking is performed to ensure that memory allocated by `operator new[]` is not freed with `free()` for example.
- The type of function performing a memory allocation is always stored along with the allocation, as well as the file and line number it was called from. If compiled with `gcc`, the function name will also be stored and the thread identifier will be stored if using the thread-safe library.
- The library uses a header file to redefine the memory allocation functions as macros in order to obtain more information about where they were called from. This is not strictly required on UNIX and Windows platforms (and AmigaOS when using `gcc`), since the library automatically redefines the default system memory allocation functions. All redefinitions in the header can also be disabled by defining the `NDEBUG` preprocessor macro, which also disables the effect of calling any mpatrol library function.
- A command is supplied to run a program that was linked with the mpatrol library with any specified options on the command line. On some UNIX platforms, an option also exists to override the default memory allocation routines for any dynamically-linked program that was not previously linked with the mpatrol library.
- The mpatrol library can be built to liaise with Parasoft Inuse, a commercial graphical memory usage tool that can display the current memory map of a running process. Inuse is supplied with Parasoft Insure++.

- Comes with a library of tools that are built on top of the mpatrol library and can be used to extend it for specific applications.
- An Automake macro is provided to ease the integration of mpatrol into a new or existing project.
- A small tool is provided to read a dictionary file and display all of the words that can be represented in hexadecimal form. Such hexadecimal constants can be used to initialise variables in user programs in order to aid debugging.
- Build scripts are supplied to build both installation packages and binary distributions. A Linux Software Map file is also provided.
- A small test suite is provided in order to test basic features.
- User documentation is currently available in TeXinfo format as well as UNIX manual pages and a quick reference card.

3 Installation

The mpatrol library was initially developed on an Amiga 4000/040 running AmigaOS 3.1. I then installed Red Hat Linux 5.1 on my Amiga and added support for Linux/m68k. I've now just recently purchased a Dell Inspiron 7500 Notebook PC and put my Amiga in retirement, so development will now continue on Red Hat Linux 6.2 and above on the Intel platform. I've tried my best to make it as easy as possible to build and install mpatrol on any system, but it isn't likely to run smoothly for everybody. However, there shouldn't be any major problems if you perform the following steps.

1. Go into the '`build`' directory and then into the appropriate subdirectory for your system.
2. Edit the '`Makefile`' in that directory and check that it is using the appropriate compiler and build tools. The `CC` macro specifies the compiler[1], the `AR` macro specifies the tool used to build the archive library and the `LD` macro specifies the tool to build the shared library. The `CFLAGS` macro specifies compiler options that are always to be used, the `OFLAGS` macro specifies optimisation options for the compiler, the `SFLAGS` macro specifies options to be passed to the compiler when building a shared library and the `TFLAGS` macro specifies options to be passed to the compiler when building a thread-safe library. You may also need to change the library names and library build commands on different systems.
3. Use the `make` command (or equivalent) to build the mpatrol library in archive form. The '`all`' target builds all possible combinations of the mpatrol library for your system. The '`clean`' target removes all relevant object files from the current directory, while the '`clobber`' target also removes all libraries that have been built from the current directory. On some UNIX platforms, the '`lint`' target will build a `lint` library for the mpatrol library.
4. If the mpatrol library is to be built with support for Parasoft Inuse then the `MP_INUSE_SUPPORT` preprocessor macro must be defined in the `CFLAGS` portion of the '`Makefile`' before building. This will ensure that Inuse will be notified of every memory allocation, reallocation and deallocation, but the Insure++ runtime library will also have to be linked in with any program that uses mpatrol.
5. Copy all of the libraries that have been built into your local library directory. If there were symbolic links created in the '`build`' directory then these should be recreated in the local library directory rather than simply copying them.
6. Copy the `mpatrol`, `mprof`, `mptrace` and `mleak` programs that have been built into your local bin directory. You may also wish to copy the `mpsym`, `mpedit` and `hexwords` commands to your local bin directory as well if your system supports Bourne shell scripts.
7. Go up two directory levels into the '`src`' directory and copy the '`mpatrol.h`', '`mpalloc.h`' and '`mpdebug.h`' header files into your local include directory.
8. Go up one directory level into the '`tools`' directory and copy all of the header files into the '`mpatrol`' subdirectory (which you'll need to create) in your local include directory.
9. On UNIX platforms, go up one directory level into the '`man`' directory and copy the '`man1`' and '`man3`' subdirectories to your local man directory. Unfortunately, the location for manual pages varies from system to system so you may or may not also be able to copy the '`cat1`' and '`cat3`' subdirectories as well. The '`man*`' subdirectories contain the unformatted manual pages while the '`cat*`' subdirectories contain the formatted manual pages.
10. Go up one directory level into the '`doc`' directory and examine the files located there. The '`mpatrol.texi`' file contains the TEXinfo source for this manual and can be translated into a wide variety of documentation formats. The '`refcard.tex`' file contains the LaTEX source for the quick reference card and can be translated into formats suitable for printing onto a few pages. There should already be translated files in the '`doc`' directory, but if not you

[1] On many systems this actually a C++ compiler by default, and should be a C++ compiler if you wish to use the C++ operators.

will have to generate them yourself using the 'Makefile' provided. You can then install or print these documents.

If you are not installing on a system that supports UNIX manual pages then you should also check in the 'man' directory to ensure that there are alternative formats for the mpatrol manual pages that you can install. If not, you will have to generate them yourself using the 'Makefile' provided.

Alternatively, the 'pkg' directory contains files that can be used to automatically generate a *package* in a specific format suitable for installation on a system. Three package formats (PKG, SD/UX and RPM) and three archive formats are currently supported (generic tape archive, LhA and ZIP). The first package format is generally used on UNIX SVR4 systems, while the second is used on HP/UX systems and the third was introduced by Red Hat for use in their Linux distributions. The generic tape archive can be used as a distribution for UNIX systems where no package format is supported, but it does not contain information on how to install the files on the system once they have been extracted from the distribution. The LhA and ZIP formats are also roughly the same, but the LhA format is intended for Amiga systems and is used for Aminet distributions, while the ZIP format is intended for Windows systems and is used for WinSite distributions. You should really know what you are doing before you attempt to build a package, and you should also be aware that some of the package files may need to be modified before you begin.

In addition, a Linux Software Map index file exists in the 'pkg/lsm' directory.

4 Integration

This section describes how to go about adding or removing the mpatrol library from your code. There are several levels for each category so it is worth reading about each before proceeding.

4.1 Adding mpatrol

The following steps should allow you to easily integrate the mpatrol library into an existing application, although some of them may not be available to do on many platforms. They are listed in the order of number of changes required to modify existing code — the last step will require a complete recompilation of all your code.

1. This step is currently only available on DYNIX/ptx, FreeBSD, IRIX, Linux, NetBSD, OpenBSD and Solaris platforms and on DG/UX 4.20MU07[1] or later platforms with the `LD_PRELOAD` feature.

   If your program or application has been dynamically linked with the system C library (‘`libc.so`’) or an alternative malloc shared library then you can use the ‘`--dynamic`’ option to the ‘`mpatrol`’ command to override the default definitions of `malloc()`, etc. at run-time without having to relink your program. If your program is multithreaded then you must also add the ‘`--threads`’ option to pick up the multithreaded shared libraries instead.

   For example, if your program’s executable file is called ‘`testprog`’ and it accepts an option specifying an input file, you can force the system’s dynamic linker to use mpatrol’s versions of `malloc()`, etc. instead of the default versions by typing:

   ```
   mpatrol --dynamic ./testprog -i file
   ```

   The resulting log file should be called ‘`mpatrol.<procid>.log`’ by default (where *procid* is the current process id), but if no such file exists after running the ‘`mpatrol`’ command then it will not be possible to force the run-time linking of mpatrol functions to your program and you will have to proceed to the next step. Note that the `mpatrol` command overrides any previous setting of the `MPATROL_OPTIONS` environment variable.

2. This step is currently only available on UNIX and Windows platforms (and AmigaOS when using `gcc`).

   You should be able to link in the mpatrol library when linking your program without having to recompile any of your object files or libraries, but this will only be worthwhile on systems where stack tracebacks are supported, otherwise you should proceed to the next step since there will not be enough information for you to tell where the calls to dynamic memory allocation functions took place.

   Information on how to link the mpatrol library to an application is given at the start of the examples (see Chapter 12 [Examples], page 75), but you should note that if your program does not directly call any of the functions in the mpatrol library then it will not be linked in and you will not see a log file being generated when you run it. You can force the linking of the mpatrol library by causing `malloc()` to be undefined on the link line, usually through the use of the ‘`-u`’ linker option.

3. All of the following steps will require you to recompile some or all of your code so that your code calls dynamic memory allocation functions from the mpatrol library rather than the system C library.

   This first step is only available when using `gcc`.

   You can make use of the `gcc` option ‘`-fcheck-memory-usage`’ which instructs the compiler to place calls to error-checking functions before each access to memory. This can result

[1] Also available on DG/UX 4.20MU05 with patch dgux_R4.20MU05.p59 and DG/UX 4.20MU06 with patch dgux_R4.20MU06.p08.

in a dramatic slowdown of your code so you may wish to limit the use of this option to a few source files, but it does provide a very thorough method of ensuring that you do not access memory beyond the bounds of a memory allocation or attempt to access free memory. However, be aware that the checks are only placed in the bodies of functions that have been compiled with this option and are missing from all functions that have not. You must link in the mpatrol library when using this option, otherwise you will get linker errors.

The '`-fcheck-memory-usage`' option was added to `gcc` to support GNU Checker, which can be considered to be the run-time system for this option. GNU Checker also includes the ability to detect reads from uninitialised memory, something that mpatrol does not currently support, and deals with stack objects as well. GNU Checker cannot be used in conjunction with mpatrol.

4. For this step, if you have a rough idea of where the function calls lie that you would like to trace or test, you need only recompile the relevant source files. You should modify these source files to include the '`mpatrol.h`' header file before any calls to dynamic memory allocation or memory operation functions.

   However, you should take particular care to ensure that all calls to memory allocation functions in the mpatrol library will be matched by calls to memory reallocation or deallocation functions in the mpatrol library, since if they are unmatched then the log file will either fill up with errors complaining about trying to free unknown allocations, or warnings about unfreed memory allocations at the end of execution.

5. This step requires you to recompile all of your source files to include the '`mpatrol.h`' header file. Obviously, this will take the longest amount of time to integrate, but need not require you to change any source files if the compiler you are using has a command line option to include a specific header file before any source files.

   For example, `gcc` comes with a '`-include`' option which has this feature, so if you had to recompile a source file called '`test.c`' then the following command would allow you to include '`mpatrol.h`' without having to modify the source file:

   ```
   gcc -include /usr/local/include/mpatrol.h -c test.c
   ```

In all cases, it will be desirable to compile your source files with compiler-generated debugging information since that may be able to be used by the '`USEDEBUG`' option or the `mpsym` command. In addition, more symbolic information will be available if the executable files have not had their symbol tables stripped from them, although mpatrol can also fall back to using the dynamic symbol table from dynamically linked executable files.

Note that an Automake macro is now provided to allow you to integrate mpatrol into a new or existing project that uses the GNU Autoconf and Automake tools. It is located in '`extra/mpatrol.m4`', which should be copied to the directory containing all of the local Autoconf and Automake macros on your system, usually '`/usr/local/share/aclocal`'. The Automake macro it defines is called `AM_WITH_MPATROL`, which should be added to the libraries section in the '`configure.in`' file for your project. It takes one optional parameter specifying whether mpatrol should be included in the project ('`yes`') or not ('`no`'). This can also be specified as '`threads`' if you wish to use the threadsafe version of the mpatrol library. You can override the value of the optional parameter with the '`--with-mpatrol`' option to the resulting '`configure`' shell script.

If you are using the `AM_WITH_MPATROL` Automake macro then you may wish to use the '`mpdebug.h`' header file instead of '`mpatrol.h`'. This ensures that the `MP_MALLOC()` family of functions are always defined, even if libmpatrol or libmpalloc are unavailable. It makes use of the `HAVE_MPATROL` and `HAVE_MPALLOC` preprocessor macros that are controlled by the Automake macro, but in other respects behaves in exactly the same way as '`mpatrol.h`'.

4.2 Removing mpatrol

Once you have ironed out all of the problems in your code with the help of the mpatrol library, there will come a time where you wish to build your program without any of its debugging features, either to improve the speed that it runs at, or perhaps even for a release. Choose one of the following steps to help you remove the mpatrol library from your program (you only need to perform them if you linked your program with the mpatrol library).

1. The quickest way to remove the mpatrol library from your application is to link with libmpalloc instead of libmpatrol. This contains replacements for all of the mpatrol library functions, either implementing memory allocation or memory operation functions with the system C library, or doing nothing in the functions which perform debugging, profiling or tracing. This method is a very quick way to remove the mpatrol library but will not result in very efficient code.
2. The other option is to recompile all of the source files which include the '`mpatrol.h`' header file, but this time define the `NDEBUG` preprocessor macro. This automatically disables the redefinition of `malloc()`, etc. and prevents calls being made to any mpatrol library functions. Obviously, this option is the most time-consuming of the two, but will result in the complete removal of all references to the mpatrol library.

Note that if you used the `AM_WITH_MPATROL` Automake macro as detailed in the previous section to build your application then you should perform a clean recompilation using the '`--without-mpatrol`' option to the '`configure`' shell script in order to completely remove the mpatrol library.

Note also that if you used the '`-fcheck-memory-usage`' option of the GNU compiler to check all memory accesses then you must recompile without that option in order for your program to run at a reasonable speed.

5 Memory allocations

In the C and C++ programming languages there are generally three different types of memory allocation that can be used to hold the contents of variables. Other programming languages such as Pascal, BASIC and FORTRAN also support some of these types of allocation, although their implementations may be slightly different.

5.1 Static memory allocations

The first type of memory allocation is known as a *static memory allocation*, which corresponds to file scope variables and local static variables. The addresses and sizes of these allocations are fixed at the time of compilation[1] and so they can be placed in a fixed-sized data area which then corresponds to a section within the final linked executable file. Such memory allocations are called static because they do not vary in location or size during the lifetime of the program.

There can be many types of data sections within an executable file; the three most common are normal data, BSS data and read-only data. BSS data contains variables and arrays which are to be initialised to zero at run-time and so is treated as a special case, since the actual contents of the section need not be stored in the executable file. Read-only data consists of constant variables and arrays whose contents are guaranteed not to change when a program is being run. For example, on a typical SVR4 UNIX system the following variable definitions would result in them being placed in the following sections:

```
int a;           /* BSS data */
int b = 1;       /* normal data */
const int c = 2; /* read-only data */
```

In C the first example would be considered a *tentative* declaration, and if there was no subsequent definition of that variable in the current translation unit then it would become a *common* variable in the resulting object file. When the object file gets linked with other object files, any common variables with the same name become one variable, or take their definition from a non-tentative definition of that variable. In the former case, the variable is placed in the BSS section. Note that C++ has no support for tentative declarations.

As all static memory allocations have sizes and address offsets that are known at compile-time and are explicitly initialised, there is very little that can go wrong with them. Data can be read or written past the end of such variables, but that is a common problem with all memory allocations and is generally easy to locate in that case. On systems that separate read-only data from normal data, writing to a read-only variable can be quickly diagnosed at run-time.

5.2 Stack memory allocations

The second type of memory allocation is known as a *stack memory allocation*, which corresponds to non-static local variables and call-by-value parameter variables. The sizes of these allocations are fixed at the time of compilation but their addresses will vary depending on when the function which defines them is called. Their contents are not immediately initialised, and must be explicitly initialised by the programmer upon entry to the function or when they become visible in scope.

Such memory allocations are placed in a system memory area called the *stack*, which is allocated per process[2] and generally grows down in memory. When a function is called, the state of the calling function must be preserved so that when the called function returns, the calling function can resume execution. That state is stored on the stack, including all local variables and parameters. The compiler generates code to increase the size of the stack upon

[1] Or more accurately, at link time.

[2] Or per thread on some systems.

entry to a function, and decrease the size of the stack upon exit from a function, as well as saving and restoring the values of registers.

There are a few common problems using stack memory allocations, and most generally involve uninitialised variables, which a good compiler can usually diagnose at compile-time. Some compilers also have options to initialise all local variables with a bit pattern so that uninitialised stack variables will cause program faults at run-time. As with static memory allocations, there can be problems with reading or writing past the end of stack variables, but as their sizes are fixed these can usually easily be located.

5.3 Dynamic memory allocations

The last type of memory allocation is known as a *dynamic memory allocation*, which corresponds to memory allocated via `malloc()` or `operator new[]`. The sizes, addresses and contents of such memory vary at run-time and so can cause a lot of problems when trying to diagnose a fault in a program. These memory allocations are called dynamic memory allocations because their location and size can vary throughout the lifetime of a program.

Such memory allocations are placed in a system memory area called the *heap*, which is allocated per process on some systems, but on others may be allocated directly from the system in scattered blocks. Unlike memory allocated on the stack, memory allocated on the heap is not freed when a function or scope is exited and so must be explicitly freed by the programmer. The pattern of allocations and deallocations is not guaranteed to be (and is not really expected to be) linear and so the functions that allocate memory from the heap must be able to efficiently reuse freed memory and resize existing allocated memory on request. In some programming languages there is support for a *garbage collector*, which attempts to automatically free memory that has had all references to it removed, but this has traditionally not been very popular for programming languages such as C and C++, and has been more widely used in functional languages like ML[3].

Because dynamic memory allocations are performed at run-time rather than compile-time, they are outwith the domain of the compiler and must be implemented in a run-time package, usually as a set of functions within a linker library. Such a package manages the heap in such a way as to abstract its underlying structure from the programmer, providing a common interface to heap management on different systems. However, this *malloc library* must decide whether to implement a fast memory allocator, a space-conserving memory allocator, or a bit of both. It must also try to keep its own internal tables to a minimum so as to conserve memory, but this means that it has very little capability to diagnose errors if any occur.

In some compiler implementations there is a builtin function called `alloca()`. This is a dynamic memory allocation function that allocates memory from the stack rather than the heap, and so the memory is automatically freed when the function that called it returns. This is a non-standard feature that is not guaranteed to be present in a compiler, and indeed may not be possible to implement on some systems[4]. However, the mpatrol library provides a debugging version of this function (and a few other related functions) on all systems, so that they make use of the heap instead of the stack.

As can be seen from the above paragraphs, dynamic memory allocations are the types of memory allocations that can cause the most problems in a program since almost nothing about them can be used by the compiler to give the programmer useful warnings about using uninitialised variables, using freed memory, running off the end of a dynamically-allocated array, etc. It is these types of memory allocation problems that the mpatrol library loves to get its teeth into!

[3] There is currently at least one garbage collection package available for C and C++ (see Appendix J [Related software], page 181).

[4] Some compilers now support variable length arrays which provide roughly the same functionality.

6 Operating system support

Beneath every malloc library's public interface there is the underlying operating system's memory management interface. This provides features which can be as simple as giving processes the ability to allocate a new block of memory for themselves, or it can offer advanced features such as protecting areas of memory from being read or written. Some embedded systems have no operating systems and hence no support for dynamic memory allocation, and so the malloc library must instead allocate blocks of memory from a fixed-sized array. The mpatrol library can be built to support all of the above types of system, but the more features an operating system can provide it with, the more it can do.

On operating systems such as UNIX and Windows, all dynamic memory allocation requests from a process are dealt with by using a feature called *virtual memory*. This means that a process cannot perform illegal requests without them being denied, which protects the other running processes and the operating system from being affected by such errors. However, on AmigaOS and Netware platforms there is no virtual memory support and so all processes effectively share the same address space as the operating system and any other running processes. This means that one process can accidentally write into the data structures of another process, usually causing the other process to fail and bring down the system. In addition, a process which allocates a lot of memory will result in there being less available memory for other running processes, and in extreme cases the operating system itself.

6.1 Virtual memory

Virtual memory is an operating system feature that was originally used to provide large usable address spaces for every process on machines that had very little physical memory. It is used by an operating system to fool[1] a running process into believing that it can allocate a vast amount of memory for its own purposes, although whether it is allowed to or not depends on the operating system and the permissions of the individual user.

Virtual memory works by translating a virtual address (which the process uses) into a physical address (which the operating system uses). It is generally implemented via a piece of hardware called a *memory management unit*, or MMU. The MMU's primary job is to translate any virtual addresses that are referred to by machine instructions into physical addresses by looking up a table which is built by the operating system. This table contains mappings to and from *pages*[2] rather than bytes since it would otherwise be very inefficient to handle mappings between individual bytes. As a result, every virtual memory operation operates on pages, which are indivisible and are always aligned to the system page size.

Even though each process can now see a huge address space, what happens when it attempts to allocate more pages than actually physically exist, or allocate an additional page of memory when all of the physical pages are in use by it and other processes? This problem is solved by the operating system temporarily saving one or more of the least-used pages (which might not necessarily belong that that process) to a special place in the file system called a *swap file*, and mapping the new pages to the physical addresses where the old pages once resided. The old pages which have been *swapped out* are no longer currently accessible, but their location in the swap file is noted in the translation table.

However, if one of the pages that has been swapped out is accessed again, a *page fault* occurs at the instruction which referred to the address and the operating system catches this and reloads the page from the swap file, possibly having to swap out another page to make space for the

[1] Well, perhaps that's too harsh a word, but it will certainly seem that way to a process running on a 32-bit UNIX system with only 4 megabytes of physical memory, and yet it will be able to read from and write to over 4 gigabytes of virtual memory!

[2] The size of a page varies between operating systems and processor architectures, but they are generally around 4 or 8 kilobytes in size, and are always a power of two.

new one. If this occurs too often then the operating system can slow down, having to constantly swap in and swap out the same pages over and over again. Such a problem is called *thrashing* and can only really be overcome by using less virtual memory or buying more physical memory.

It is also possible to take advantage of the virtual memory system's interaction between physical memory and the file system in program code, since mapping an existing file to memory means that the usual file I/O operations can be replaced with memory read and write operations. The operating system will work out the optimum way to read and write any buffers and it means that only one copy of the file exists in both physical memory and the file system. Note that this is how *shared libraries*[3] on UNIX platforms are generally implemented, with each individual process that uses the shared library having it mapped to somewhere in its address space.

Another major feature of virtual memory is its ability to read protect and write protect individual pages of process memory. This means that the operating system can control access to different parts of the address space for each process, and also means that a process can read and/or write protect an area of memory when it wants to ensure that it won't ever read or write to it again. If an illegal memory access is detected then a *signal* will be sent to the process, which can either be caught and handled or will otherwise terminate the process. Note that as with all virtual memory operations, this ability to protect memory only applies to pages, so that it is not possible to protect individual bytes.

However, some versions of UNIX have programmable software *watch points* which are implemented at operating system level. These are normally used by debuggers to watch a specified area of memory that is expected to be read from or written to, but can just as easily be used to implement memory protection at byte level. Unfortunately, as this feature is implemented in software[4] rather than in hardware, watch points tend to be incredibly slow, mainly as a result of the operating system having to check every instruction before it is executed. In addition, some UNIX platforms only allow a certain number of software watch points to be in use at any one time, so even if your system supports them you may not be able to use them with the mpatrol library if there are many memory allocations in use at one time.

There is also an additional problem when using watch points, which is due to misaligned reads from memory. These can occur with compiler-generated code or with optimised library routines where memory read, move or write operations have been optimised to work at word level rather than byte level. For example, the `memcpy()` function would normally be written to copy memory a byte at a time, but on some systems this can be improved by copying a word at a time. Unfortunately, care has to be taken when reading and writing such words as the equivalent bytes may not be aligned on word boundaries. Technically, reading additional bytes before or after a memory allocation when they share the same word is legal, but when using watch points such errors will be picked up. The mpatrol library replaces most of the memory operation functions provided by the system libraries with safer versions, although they may not be as efficient.

An operating system with virtual memory is usually going to run ever so slightly slower than an operating system without it[5], but the advantages of virtual memory far outweigh the disadvantages, especially when used for debugging purposes.

6.2 Call stacks and symbol tables

As stated in the section on stack memory allocations (see Section 5.2 [Stack memory allocations], page 19), when a function is called, a copy of the caller's state information (including

[3] DLLs on Windows platforms.

[4] The operating system is still considered software.

[5] Due to the overhead of having to translate every address and swap in and out pages — although memory mapped files will usually be more efficient than using normal file operations on a system without virtual memory.

local variables and registers) is saved on the stack so that it can be restored when the called function returns. On many operating systems there is a *calling convention*[6] which defines the layout of such stack entries so that code compiled in different languages and with different compilers can be intermixed. This usually specifies at which stack offsets the stack pointer, program counter and local variables for the calling function can be found, although on some processor architectures the function calling conventions are specified by the hardware and so the operating system must use these instead.

On systems that have consistent calling conventions, it is usually possible to perform call stack *tracebacks* from within the current function in order to determine the stack of function calls that led to the current function. This is extremely useful for debugging purposes and is done by examining the current stack frame to see if there is a pointer to the previous stack frame. If there is, then it can be followed to find out all of the state information about the calling function. This can be repeated until there are no more stack frames[7]. This is generally how this information is determined by debuggers when a call stack traceback is requested.

In addition to the pointer to the previous stack frame, the saved state information also always contains the saved program counter register, which contains either the address of the instruction that performed the function call, or the address of the instruction at which to continue execution when the called function returns[8]. This information can be used to identify which function performed the call, since the address of the instruction must lie between the start and end of one of the functions in the process.

There are several different ways to perform stack unwinding. The first requires compiler support and uses builtin functions to determine the next stack frame and the return address. The GNU C compiler, `gcc`, supports this but unfortunately the number of stack frames to traverse must be known at compile-time rather than run-time. The second method requires operating system support, with a library of routines provided to perform call stack traversal. Unfortunately, such routines can be quite time consuming and may require a lot of resources, but on the other hand they are likely to be very reliable at obtaining the necessary information. The mpatrol library can be built to support either of these methods, with the `MP_BUILTINSTACK_SUPPORT` and the `MP_LIBRARYSTACK_SUPPORT` preprocessor macros.

A third way to perform stack unwinding involves reading (or effectively disassembling) the instructions that are being executed in order to determine the size of the stack frame being used and the address of the instruction at which execution will resume when the function returns. This can also be quite a reliable method of obtaining call stack information but is only likely to be feasible on a processor architecture which has a very simple instruction set, such as a RISC[9] architecture. MIPS processors are a good example of this.

The final method of stack unwinding requires that the frame pointer and return address are both stored on the stack whenever a new function is called. The chain of frame pointers can then be followed down the stack, and the return addresses can be read at a given offset from the frame pointers. This is usually possible with CISC[10] processor architectures that have dedicated call instructions which automatically save such information on the stack, although some RISC processors also save these as well. However, inline functions and compiler optimisations can sometimes result in the frame pointer being omitted, usually resulting in an inability to walk the stack.

However, in order to determine this symbolic information, it must be possible to find out where the start and end addresses of all of the functions in the process are. This can usually only be read from object files, since they contain the symbol tables that were used by the linker to generate the final executable file for the program. The object file's symbol tables normally

---

[6] Usually part of the *Application Binary Interface*, or ABI.

[7] A process also known as *stack unwinding*.

[8] Also known as the *return address*.

[9] Reduced Instruction Set Computer.

[10] Complex Instruction Set Computer.

contain information about the start address, size, name and visibility of every symbol that was defined, but this depends on the format of the object file and if the symbol tables have been stripped from the final executable file.

If the object file was created by a compiler then it may also contain debugging information that was generated by the compiler for use with a debugger. Such information may include a mapping of code addresses to source lines[11], and this information can be used by the mpatrol library to provide more meaningful information in call stack tracebacks.

On systems that support shared libraries, additional work must be done to determine the symbolic information for all of the functions which have been defined in them. The symbols for functions that are defined in shared libraries normally appear as undefined symbols in the executable file for the program and so must be searched in the system in order to get the necessary information. It is usually necessary to liaise with the *dynamic linker*[12] on many systems.

6.3 Threads

On systems with virtual memory, such as UNIX and Windows, user programs are run as *processes* which have their own address space and resources. If a process needs to create sub-processes to perform other tasks it must call `fork()` or `spawn()` to create new processes, but these new processes do not share the same address space or resources as the parent process. If processes need to share memory they must either use a message passing interface or explicitly mark a range of memory as shareable.

Traditionally, this was not too much of a handicap as parallel processing was an expensive luxury and could only be made use of by the kernel of such systems. However, with the birth of fast processors and parallel programming, programs could be made to run more efficiently and faster on multi-processor systems by having more than one *thread* of control. This was achieved by allowing processes to have more than one program counter through which the processor could execute instructions, and if one thread of control stalled for a particular reason then another could continue without stalling the entire process.

Such multithreaded programs allow parallel programming and implicit shared memory between threads since all threads in a process share the same address space and resources. This is similar to operating systems that have no virtual memory, such as AmigaOS and Netware[13], except that once a process terminates, all threads terminate as well and all of its resources are still reclaimed.

Multithreaded programming generally needs no compiler support, but does require some primitive operations to be supported by the operating system for a threads library to call. The functions that are available in the threads library provide the means for a process to create and destroy threads. There are currently several popular threads libraries available, although the POSIX threads standard remains the definitive implementation.

It is always important to remember when programming a multithreaded application that because all threads in a process share the same address space, measures must be taken to prevent threads reading and writing global data in a haphazard fashion. This can either be done by locking with semaphores and mutexes, or can be performed by using stack variables instead of global variables since every thread has its own local stack. Care must be taken to write re-entrant functions — i.e. a function will give exactly the same result with one thread as it will with multiple threads running it at the same time.

The mpatrol library can be built as a thread-safe library with support for multi-threaded programs. When this library is linked with your program, only one thread at a time can allocate, reallocate or deallocate dynamic memory, or perform a memory operation via `memcpy()`,

---

[11] Generally known as a line number table.

[12] Which is the part of the operating system that performs the run-time linking of shared libraries.

[13] Where the kernel is effectively a single process running all user programs as threads.

`memset()`, etc. This does not take full advantage of the potential concurrency in the library, but at least it will allow the debugging of multi-threaded programs.

The process of making the mpatrol library thread-safe was made more complicated by the fact that the mutexes protecting the library's data structures had to be recursive, since some of the functions that the library will call may call `malloc()` and `free()` or any other functions redefined by the library. If this was to happen with non-recursive mutexes then the recursive call would result in the thread attempting to lock a mutex that it already owned. However, implementing recursive mutexes was only half the problem.

The other problem with writing a thread-safe malloc library is that it must be initialised before the program becomes multi-threaded. If the library is initialised when there are multiple threads running then one thread may be attempting to initialise the mutexes whilst another thread may be attempting to lock an uninitialised mutex. Ideally, the best place to initialise the library would be at the start of `main()` but there is currently no way to do this other than getting users to explicitly plant calls to initialise the library in their code. This is not a very satisfactory solution if all we want to do is link in the replacement malloc library without any need for recompilation.

Fortunately, there are some ways to plant initialisation calls before `main()` is called, but they all have some drawbacks. The first way is to use a static file-scope constructor in C++, which will then initialise the mutexes and the library data structures before the code in `main()` is executed. However, on many systems this will require the final link to be performed by the C++ compiler that built the library. That may not be desirable or even possible in many cases. Unfortunately, this drawback appears in the second method, which involves using the GNU C compiler to compile the library. This compiler has an extension which allows functions to be specified as constructors which will be called before `main()`, but means that any program which is linked with the resulting library must be linked with the GNU C compiler driver. However, many systems are now GNU-based which would mean that this would happen anyway.

The final way of initialising the mutexes and the library data structures is to plant a call to the initialisation routines from a special section which the system will call before `main()` is called. This section is called the '`.init`' section on ELF-based platforms, but may exist in another form on other platforms too. This has the advantage that the system linker can be used to link the final program, but a possible disadvantage is that the library may be initialised too early, possibly before the environment or file streams have been set up. You may find that if one of the above methods does not work for you then perhaps another one will.

7 Using mpatrol

This chapter contains a general description of all of the features of mpatrol and how to use them effectively. You'll also find a complete reference for mpatrol in the appendices, but you may wish to try out the examples (see Chapter 12 [Examples], page 75) and the tutorial (see Chapter 13 [Tutorial], page 109) before reading further.

7.1 Library behaviour

Most of the behaviour of the mpatrol library can be controlled at run-time via options which are read from the `MPATROL_OPTIONS` environment variable. This prevents you having to recompile or relink each time you want to change a library setting, and so makes it really easy to try out different settings to locate a particular bug. You should know how to set the value of an environment variable on your system before you read on.

By default, the mpatrol library will attempt to determine the minimum required alignment for any generic memory allocation when it first initialises itself. This may be affected by the compiler and its settings when the library was built but it should normally reflect the minimum alignment required by the processor on your system. If you would prefer a larger (or perhaps even smaller) default alignment you may change it at run-time using the '`DEFALIGN`' option. The value you supply must be in bytes, must be a power of two, and should not be larger that the system page size. If you encounter bus errors due to misaligned memory accesses then you should increase this value.

On systems that have virtual memory the library will attempt to write-protect all of its internal structures when user code is being run. This ensures that it is nearly impossible for a program to corrupt any mpatrol library data. However, unprotecting and then protecting the structures at every library call has a slight overhead so you may prefer to disable this behaviour by using the '`NOPROTECT`' option. This has no effect on systems that have no virtual memory.

Usually it is desirable for many system library routines to be protected from being interrupted by certain signals since they may themselves be called from signal handlers. If this is not the case then it may be possible to interrupt the program from within such routines, perhaps causing problems if their global variables are left in an undefined state. As the mpatrol library replaces some of these system library routines it is also possible to specify that they are protected from certain interrupt signals using the '`SAFESIGNALS`' option. However, this can sometimes result in it being hard to interrupt the program from the keyboard if a lot of processor time is spent in mpatrol routines, which is why this behaviour is disabled by default[1].

On UNIX systems, the usual way for malloc libraries to allocate memory from the process heap is through the `sbrk()` system call. This allocates memory from a contiguous heap, but has the disadvantage in that other library functions may also allocate memory using the same function, thus creating holes in the heap. This is not a problem for mpatrol, but you may have a suspicion that your bug is due to a function from another library corrupting your data so you may wish to use the '`USEMMAP`' option. This is only available on systems that have the `mmap()` system call and allows mpatrol to allocate all of its memory from a part of the process heap that is non-contiguous (i.e. each call to `mmap()` may return a block of memory that is completely unrelated to that returned by the previous call). It may also be required on some systems in order for the mpatrol library to implement memory protection.

Beginning with release 1.3.3, the mpatrol library now allocates its internal memory in the opposite way to user memory on UNIX systems that support the `mmap()` system call. This means that by default, user memory is allocated with `sbrk()` whereas internal memory is allocated with `mmap()`, and this behaviour is reversed when the '`USEMMAP`' option is used. This was done

[1] In mpatrol release 1.0 it was enabled by default.

to segregate user memory from internal memory, and was especially required for the `mptrace` command's graphical display.

The '`CHECK`' option allows you to specify that every time an mpatrol library function is called the library will automatically check the freed memory and overflow buffers of every memory allocation, although this can slow program execution down, especially if you suspect the error you are looking for occurs at the 1000th memory allocation, for example. You can therefore use the '`CHECK`' option to specify a range of memory allocations at which the mpatrol library will automatically check the freed memory and overflow buffers. All other allocations that fall outside this range will not be checked. You can also specify an optional frequency at which this checking should be performed. No such checking is performed by default in mpatrol release 1.4.0 and onwards — you must specify '`CHECK=-`' to get the original behaviour.

On UNIX systems, the mpatrol library can also invoke the `mpedit` command to edit source files that show up in any warnings or error messages that it generates. This can only happen if the diagnostic message can be traced back to a specific source line in the program; in many cases this is not possible. If editing the files is not required, a context listing of the appropriate source line can be generated instead. The '`EDIT`' option specifies that files are to be edited and the '`LIST`' option specifies that a context listing is to be generated. These options are mutually exclusive.

If the mpatrol library that was built for your system supports reading symbolic information from a program's executable file, but it cannot locate the executable file, or you wish to specify an alternative, you can use the '`PROGFILE`' option to do this. All this does is instruct the mpatrol library to read symbols from this file instead. Note that on systems that support dynamic linking, the library can also read symbols from a dynamically linked executable file that has had its normal symbol table stripped.

Finally, a list of all of the recognised options in the mpatrol library can be displayed to the standard error file stream by using the '`HELP`' option. This will not affect the settings of the library in any way, so you should be able to use other options at the same time.

7.2 Logging and tracing

If you would like to see a complete log of all of the memory allocations, reallocations and deallocations performed by your program, use the '`LOGALL`' option. This provides detailed tracing for each of the mpatrol library functions, and a full description of the format of such tracing is given in Example 1 (see Section 12.1 [Example 1], page 76). Alternatively, you may select one or more types of functions to be traced using the '`LOGALLOCS`', '`LOGREALLOCS`', '`LOGFREES`' and '`LOGMEMORY`' options if you feel that the log file is too large when '`LOGALL`' is used. By default all diagnostics from the mpatrol library get sent to '`mpatrol.log`' in the current directory, but this can be changed using the '`LOGFILE`' option. In fact, you can also specify a directory where all log files from the mpatrol library will get placed by setting the `LOGDIR` environment variable.

On systems that support it, every log entry also contains a call stack traceback that may also include the names of the symbols that appear on the call stack. If the object file access library that mpatrol was built with has support for reading line number tables from object files then the '`USEDEBUG`' option will also try to determine the file name and line number for each entry in the call stack, but only if the object files contain the relevant debugging information. This information will only be available before program termination and so any call stack tracebacks that appear after the library summary will not be displayed with their corresponding file name and line number. This option will also slow down program execution since a search through the line number tables will have to be made every time a call stack is displayed. Alternatively, the `mpsym` command may be used to process an mpatrol log file with a debugger in order to obtain symbol names and source level information for any call stacks.

Because the `alloca()`, `strdupa()` and `strndupa()` functions automatically free their allocations when the calling function returns, the log entries for these types of memory allocation are slightly different. The actual memory allocation will have an entry similar to `malloc()`, etc., but the memory deallocation will be marked as being done by `alloca()` and will occur at the next call to an mpatrol library function after the calling function has returned. However, any such allocations that are explicitly deallocated with the `dealloca()` function will be marked as being done by `dealloca()`.

The mpatrol library will always try to display as much useful information as possible in this log file, and will always display a summary of library settings and statistics when your program terminates successfully. If you don't get this then your program did not call `exit()` and either called `abort()` or was terminated by the operating system instead. In such cases, either use a debugger to see where your program crashed or use the '`LOGALL`' option to see the last successful library call in the log file so that you have a rough idea of where your program crashed.

It is also possible to get mpatrol to write more summary information to the log file after it writes out its settings and statistics at program termination. Use the '`SHOWFREED`' and '`SHOWUNFREED`' options to display a list of freed and unfreed memory allocations. The former will only be displayed if the '`NOFREE`' option is used, but the latter can be useful for detecting memory leaks. The '`SHOWFREE`' option can be used to display a summary of any free memory blocks.

The '`SHOWMAP`' option will display a memory map of the heap that was valid when the process terminated, and the '`SHOWSYMBOLS`' option will display any symbolic information that the mpatrol library managed to obtain from any executable files and libraries that were relevant to the program being tested. All of the above five options can be selected with the '`SHOWALL`' option.

Because the log file can contain verbose information about memory allocations, reallocations, deallocations and operations, it can end up being too large if all such information is being logged for a large program. To get around this, it is possible to *trace* all memory allocation and deallocation events in a concise way, to be stored in a separate file for later processing by the `mptrace` command. By default, no such tracing is performed but it can be enabled with the '`TRACE`' option. The default tracing output file is '`mpatrol.trace`', but this can be changed using the '`TRACEFILE`' option. As with the '`LOGFILE`' option, you can also specify a directory where all tracing output files from the mpatrol library will get placed by setting the `TRACEDIR` environment variable.

7.3 General errors

By default, the mpatrol library follows the guidelines for ANSI C and C++ regarding the behaviour of the dynamic memory allocation and memory operation functions it replaces. This means that calling `malloc()` with a size of zero is allowed, for example. However, warnings can be generated for all of these types of calls by using the '`CHECKALL`' option. The '`CHECKALLOCS`' option warns only about calls to `malloc()` and similar functions with a size of zero, the '`CHECKREALLOCS`' option warns only about calls to `realloc()` and similar functions with either a null pointer or a size of zero, and the '`CHECKFREES`' option warns only about calls to `free()` and similar functions with a null pointer. The '`CHECKMEMORY`' option gives an error if a zero-size memory operation is performed on a '`NULL`' pointer — this is normally allowed by default.

All newly-allocated memory can be pre-filled with a specified byte by using the '`ALLOCBYTE`' option. This can be used to catch out code that expects newly-allocated memory to be zeroed, although this option will have no effect on memory that was allocated with `calloc()`. All free memory can also be pre-filled with a different specified byte by using the '`FREEBYTE`' option. This will catch out code that expects to be able to use the contents of freed memory. Note that you may wish to change these options from their default values on your system so that the contents can be filled with values that are least likely to be used at run-time. For example, ensuring that the pointer representation of the value can never be a valid pointer, or that the floating point representation will always be invalid. These values will vary across operating systems and processor architectures.

Alternatively, the mpatrol library can be instructed to keep all (or a certain number of recent) freed memory allocations so that its diagnostics can be clearer about which freed allocation a piece of code is erroneously trying to access. This is controlled with the '`NOFREE`' option, which accepts an argument specifying the maximum number of recently-freed memory allocations to prevent being reused. If the argument is zero then all freed memory allocations will be immediately reused by the mpatrol library. If the argument is non-zero then the mpatrol library will use up more memory than usual since it has to keep all of the freed memory allocations lying around until their lifetime has expired. Note that this option distinguishes between *free* memory and *freed* memory. *Free* memory is unallocated memory that has been taken from the system heap. *Freed* memory is a freed memory allocation, with all of the original details of the allocation preserved.

Normally, the '`NOFREE`' option will fill the freed allocation with the free byte so that any code that accesses it will hopefully fall over. However, the original contents can be preserved using the '`PRESERVE`' option in case you need to see what the contents were just before it was freed. The '`NOFREE`' option is also affected by the '`PAGEALLOC`' option, since then the freed allocation will have its contents both read and write protected so that nothing can access them. If the '`PRESERVE`' option is used in this case then the freed allocation will only be made write-protected so that the original contents can be read from but not written to.

Note that if the argument specified with the '`NOFREE`' option is non-zero then the mpatrol library will store all recently-freed memory allocations in a queue. Once the queue has filled to the point specified with the '`NOFREE`' option then all subsequent calls to free memory will result in the most recently-freed memory allocation being placed at the end of the queue and the freed memory allocation at the beginning of the queue will be returned to the free memory pool for later reuse. Obviously, the larger the freed queue size, the better chance of detecting attempts to access previously-freed memory, but unfortunately more memory will be used up and the mpatrol library will have to keep track of a larger number of memory allocations.

7.4 Overwrites and underwrites

Once a block of memory has been allocated, it is imperative that the program does not attempt to write any data past the end of the block or write any data just before the beginning of the block. Even writing a single byte just beyond the end of an allocation or just before the beginning of an allocation can cause havoc. This is because most malloc libraries store the details of the allocated block in the first few words before the beginning of the block, such as its size and a pointer to the next block. The mpatrol library does not do this, so a program which failed using the normal malloc library and worked when the mpatrol library was linked in is a possible candidate for turning on overflow buffers.

Such memory corruption can be extremely difficult to pinpoint as it is unlikely to show itself until the next call is made to the malloc library, or if the internal malloc library blocks were not overwritten, the next time the data is read from the block that was overwritten. If the former is the case then the next library call will cause an internal error or a crash, but only when the memory block that was affected is referenced. This is likely to disappear when using the mpatrol library since it keeps its internal structures separate, and write-protects them on systems that support memory protection.

In order to identify such errors, it is possible to place special buffers[2] on either side of every memory allocation, and these will be pre-filled with a specified byte. Before every mpatrol library call, the library will check the integrity of every such overflow buffer in order to check for a memory underwrite or overwrite. Depending on the number of allocations and size of these buffers, this can take a noticable amount of time (which is why overflow buffers are disabled by default), but can mean that these errors get noticed sooner. The option which governs this is '`OFLOWSIZE`'. The byte with which they get pre-filled can be changed with '`OFLOWBYTE`'.

[2] Commonly known as *overflow buffers* or *fence posts*.

Depending on what gets written, it might only be possible to see such errors when a different size of buffer or a different pre-fill byte is used.

Note that you may wish to change the 'OFLOWBYTE' from its default value on your system so that the contents can be filled with values that are least likely to be used at run-time. For example, ensuring that the pointer representation of the value can never be a valid pointer, or that the floating point representation will always be invalid. These values will vary across operating systems and processor architectures, but may also vary depending on the datatypes that you will be expecting to store in the memory allocations.

A worse situation can occur when it is only reads from memory that overflow or underflow; i.e. with the faulty code reading just before or just past a memory allocation. These cannot be detected by overflow buffers as it is not possible using conventional means to interrupt every single read from memory. However, on systems with virtual memory, it is possible to use the memory protection feature to provide an alternative to overflow buffers, although at the added expense of increased memory usage.

The 'PAGEALLOC' option turns on this feature and automatically rounds up the size of every memory allocation to a multiple of the system page size. It also rounds up the size of every overflow buffer to a multiple of the system page size so that every memory allocation occupies its own set of pages of virtual memory and no two memory allocations occupy the same page of virtual memory. The overflow buffers are then read and write protected so that any memory accesses to them will generate an error[3]. Following on from the previous section, the 'PAGEALLOC' option also causes free memory to be read and write protected as well since that will also occupy non-overlapping virtual memory pages.

The remaining memory that is left over within an allocation's pages is effectively turned into traditional overflow buffers, being pre-filled with the overflow byte and checked periodically by the mpatrol library to ensure that nothing has written into them. However, because of this remaining memory, the library has a choice of where to place the memory allocation within its pages. If it places the allocation at the very beginning then it will catch memory underwrites, but if it places the allocation at the very end then it will catch memory overwrites. Such a choice can be controlled at run-time by supplying an argument to the 'PAGEALLOC' option. If 'PAGEALLOC=LOWER' is used then every allocation will be placed at the very beginning of its pages and if 'PAGEALLOC=UPPER' is used then the placement will be at the very end of its pages. This is probably better explained in Example 3 (see Section 12.3 [Example 3], page 86) where the problems with 'PAGEALLOC=UPPER' and alignment are also discussed.

Obviously, there are still some deficiencies when using 'PAGEALLOC' since it can use up a huge amount of memory (especially with 'NOFREE') and the overflow buffers within an allocation's pages can still be read without causing an immediate error. Both of these deficiencies can be overcome by using the 'OFLOWWATCH' option to install *software watch points* instead of overflow buffers, but there are still very few systems that support software watch points at the moment, and it can slow a program's execution speed down by a factor of around 10,000. The reason for this is that software watch points instruct the operating system to check every read from and write to memory, which means that it has to single-step through a process checking every instruction before it is executed. However, this is a very thorough way of checking for overflows and is unlikely to miss anything, although there may be problems with misaligned memory accesses when using watch points (see Section 6.1 [Virtual memory], page 21).

Note that from release 1.1.0 of mpatrol, the library comes with replacement functions for many memory operation functions, such as `memset()` and `memcpy()`. These new functions provide additional checks to ensure that if a memory operation is being performed on a memory block, the operation will not read or write before or beyond the boundaries of that block.

Normally, if an error is discovered in the call to such functions, the mpatrol library will report the error but prevent the operation from being performed before continuing execution. If the

[3] This is a feature that was first used by Electric Fence (see Appendix J [Related software], page 181) to track down memory corruption.

error was that the range of memory being operated on overflowed the boundaries of an existing memory allocation then the 'ALLOWOFLOW' option can be used to turn the error into a warning and force the operation to continue. This behaviour can be desirable in certain cases where third-party libraries are being used that make such calls but the end result does not overflow the allocation boundary.

From release 1.3.3 of mpatrol, the library comes with functions that interface to the '-fcheck-memory-usage' option of the GNU compiler. This option instructs the compiler to place error-checking calls before each read or write to memory. The functions that are called then check to ensure that the memory access does not overflow a heap memory allocation or access free memory. This can be a very useful way to go through your code looking for errors with a fine tooth-comb, but be aware that it does slow down execution by a large factor. It also only affects functions that were compiled with this option, so if the problem lies in a function that was not recompiled with '-fcheck-memory-usage' then it won't do much good.

To conclude, if you suspect your program has a piece of code which is performing illegal memory underwrites or overwrites to a memory allocation you turn on the 'CHECK=-' option and you should use each of the following options in sequence, but only if your system supports them. If all else fails and you are using the GNU compiler then you could try recompiling some or all of your code with the '-fcheck-memory-usage' option.

1. 'OFLOWSIZE=8'
2. 'OFLOWSIZE=32'
3. 'OFLOWSIZE=1' 'PAGEALLOC=LOWER'
4. 'OFLOWSIZE=1' 'PAGEALLOC=UPPER'
5. 'OFLOWSIZE=8' 'OFLOWWATCH'
6. 'OFLOWSIZE=32' 'OFLOWWATCH'

7.5 Using with a debugger

If you would like to use mpatrol to pause at a specific memory allocation, reallocation or deallocation in a debugger then this section will describe how to go about it. Unfortunately, debuggers vary widely in function and usage and are normally very system-dependent. The example below will use gdb as the debugger, but as long as you know how to set a breakpoint within a debugger, any one will do.

First of all, decide where you would like the mpatrol library to pause when running your program within the debugger. You can choose one allocation index to break at using the 'ALLOCSTOP' option, or you can choose to break at a specific reallocation of that allocation by also using the 'REALLOCSTOP' option. If you use 'REALLOCSTOP' without using 'ALLOCSTOP' then you will break at the first memory allocation that has been reallocated the specified number of times. You can also choose to break at the point in your program that frees a specific allocation index by using the 'FREESTOP' option.

The normal process for determining where you would like to pause your program in the debugger is by using the 'LOGALL' option and examining the log file produced by mpatrol. If your program crashed then you should look at the last entry in the log file to see what the allocation index (and possibly also the reallocation index) of the last successful call was. You can then decide which of the above options to use. Note that the debugger will break at a point before any work is done by the mpatrol library for that allocation index so that you can see if it was the last successful operation that caused the damage.

Having decided which combination of mpatrol options to use, you should set them in the MPATROL_OPTIONS environment variable before running the debugger on your program. Alternatively, your debugger may have a command that allows you to modify your environment during debugging, but you're just as well setting the environment variable before you run the debugger as it shouldn't make any difference[4].

After you get to the debugger command prompt, you should set a breakpoint at the `__mp_trap()` function. This is the function that gets called when the specified allocation index and/or reallocation index appears and so when you run your program under the debugger the mpatrol library will call `__mp_trap()` and the debugger will stop at that point. If you are not running your program within a debugger, or if you haven't set the breakpoint, then `__mp_trap()` will still be called, but it won't do anything. Note that there may be some naming issues on some platforms where the visible name of a global function gets an underscore prepended to it. You may have to take that into account when setting the breakpoint on such systems.

Now that you have set the `MPATROL_OPTIONS` environment variable and have set the debugger to break at `__mp_trap()`, all that is required is for you to run your program. Hopefully, the debugger should stop at `__mp_trap()`. If it doesn't then you may have to check your environment variable settings to ensure that they are the same as when you ran the program outwith the debugger, although obviously with the addition of '`ALLOCSTOP`', etc. Once the program has been halted by the debugger, you can then single-step through your code until you see where it goes wrong. If this is near the end of your program then you'll have saved yourself a lot of time by using this method.

The following example will be used to illustrate the steps involved in using the '`ALLOCSTOP`', '`REALLOCSTOP`' and '`FREESTOP`' options. However, it is only for tutorial purposes and the same effect could easily be achieved by breaking at line 18 in a debugger because in this case it is obvious from the code and the mpatrol log file where it is going wrong. In real programs this is hardly ever the case[5].

```
 1  /*
 2   * Allocates 1000 blocks of 16 bytes, freeing each block immediately
 3   * after it is allocated, and freeing the last block twice.
 4   */


 7  #include "mpatrol.h"


10  int main(void)
11  {
12      void *p;
13      int i;

15      for (i = 0; i < 1000; i++)
16          if (p = malloc(16))
17              free(p);
18      free(p);
19      return EXIT_SUCCESS;
20  }
```

Compile this example code with debugging information enabled and link it with the mpatrol library, then set `MPATROL_OPTIONS` to '`LOGALL`' and run the resulting program. If you examine '`mpatrol.log`' you will see the following near the bottom of the file.

```
...
```

[4] Unless you've linked the debugger with the mpatrol library.

[5] The other reason that this program is simple is because a proper example would generally involve crashing the program, but on AmigaOS and Netware that would also involve crashing the system — not something you'd want to do whilst trying this out.

```
ALLOC: malloc (1000, 16 bytes, 4 bytes) [main|test.c|16]
        0x08049449 main+57
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

returns 0x080620E8

FREE: free (0x080620E8) [main|test.c|17]
        0x08049470 main+96
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

    0x080620E8 (16 bytes) {malloc:1000:0} [main|test.c|16]
        0x08049449 main+57
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

FREE: free (0x080620E8) [main|test.c|18]
        0x08049491 main+129
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

ERROR: [NOTALL]: free: 0x080620E8 has not been allocated

...
```

In this example, we'll want to use 'ALLOCSTOP' to halt the program at the 1000th memory allocation so that we can step through it with a debugger. So, set MPATROL_OPTIONS to 'ALLOCSTOP=1000' and load the program into the debugger. If you are using gdb you can now do the following steps, but if you are not you will have to use the equivalent commands in your debugger. Note that '(gdb)' is the debugger command prompt and so anything that appears on that line after that should be typed as a command.

```
(gdb) break __mp_trap
Breakpoint 1 at 0x804ee83
(gdb) run
Starting program: a.out
Breakpoint 1, 0x804ee83 in __mp_trap()
(gdb) backtrace
#0  0x804ee83 in __mp_trap()
#1  0x804c61b in __mp_getmemory()
#2  0x8049894 in __mp_alloc()
#3  0x8049449 in main() at test.c:16
(gdb) finish
Run till exit from #0  0x804ee83 in __mp_trap()
0x804c61b in __mp_getmemory()
(gdb) finish
Run till exit from #0  0x804c61b in __mp_getmemory()
0x8049894 in __mp_alloc()
(gdb) finish
Run till exit from #0  0x8049894 in __mp_alloc()
0x8049449 in main() at test.c:16
```

```
16              if (p = malloc(16))
(gdb) step
17                  free(p);
(gdb) step
15          for (i = 0; i < 1000; i++)
(gdb) step
18          free(p);
(gdb) quit
The program is running.  Exit anyway? (y or n) y
```

After setting the breakpoint and running the program, the debugger halts at `__mp_trap()`. Because `__mp_trap()` is a function within the mpatrol library, you don't want to bother stepping through any of the library functions, and in this case you can't since the mpatrol library was not compiled with debugging information enabled. So, after returning from all of the library functions, the source line becomes line 16 because that was the location of the 1000th memory allocation. Single-stepping twice gets us to line 18 which is our destination. Note that the file '`extra/.gdbinit`' included in the mpatrol distribution contains predefined commands which make setting the allocation index to stop at much easier.

Sometimes it is useful to be able to see information about a memory allocation whilst running a program from within a debugger. The `__mp_printinfo()` function is provided for that purpose and takes a heap address as its only argument. Using the above example, it would have been possible to print out information about the pointer '`p`' at line 17 from within `gdb`:

```
(gdb) call __mp_printinfo(p)
address 0x080620E8 located in allocated block:
    start of block:     0x080620E8
    size of block:      16 bytes
    stored type:        <unknown>
    stored type size:   <unknown>
    user data:          0x00000000
    allocated by:       malloc
    allocation index:   1000
    reallocation index: 0
    modification event: 1999
    calling function:   main
    called from file:   test.c
    called at line:     16
    function call stack:
        0x08049449 main
        0x4007C9CB __libc_start_main
        0x08049381 _start
```

Some debuggers, such as `gdb`, also allow you to define your own commands for use in a debugging session. The following example defines a new `gdb` command called '`printalloc`' which calls `__mp_printinfo()`[6]:

```
(gdb) define printalloc
Type commands for definition of "printalloc".
End with a line saying just "end".
>call __mp_printinfo($arg0)
>end
(gdb) document printalloc
Type documentation for "printalloc".
```

[6] A sample GDB command file for use with mpatrol can be found in '`extra/.gdbinit`'.

```
End with a line saying just "end".
>Displays information about an address in the heap.
>end
```

7.6 Testing

The mpatrol library has several features that make it useful when testing a program's dynamic memory allocations. These are features that do not help in fixing an existing bug, but rather help to identify additional bugs that may be lurking in your code.

It is possible to set a simulated upper limit on the amount of heap memory available to a process with the '`LIMIT`' option, which accepts a size in bytes, but will be disabled when it is zero. This can be extremely useful for testing a program under simulated low memory conditions to see how it handles such errors. Of course, you should set the heap limit to a value less than the amount of actual available memory otherwise this option will have no effect. Note that the mpatrol library may use up a small amount of heap memory when it initialises itself[7] so the value passed to the '`LIMIT`' option may need to be set slightly higher than you would normally expect.

It is also possible to instruct the mpatrol library to randomly fail a certain number of memory allocations so that you can further test error handling code in a program. The frequency at which failures occur can be controlled with the '`FAILFREQ`' option, where a value of zero means that no failures will occur, but any other value will randomly cause failures. For example, a value of '`10`' will cause roughly one in ten failures and a value of '`1`' will cause every memory allocation to fail. The random sequence can be made predictable by using the '`FAILSEED`' option. If this is non-zero then the same program run with the same failure frequency and same failure seed will fail on exactly the same memory allocations. If this is zero then the failure seed will itself be set randomly, but you can see its value when the summary is displayed at program termination.

When running *batch tests*[8] it is sometimes useful to be able to detect if there have been any memory leaks. Such leaks should normally be distinguished from code which has purposely not freed the memory that it allocated, so there may be a certain expected number of unfreed allocations at program termination. It may be that you would like to highlight any additional unfreed allocations since they may be due to real memory leaks, so the '`UNFREEDABORT`' option can be set to a threshold number of expected unfreed allocations. If the library detects a number of unfreed allocations higher than this then it will abort the program at termination so that it fails. All tests that fail in this way can then be examined after the test suite finishes.

7.7 Library functions

Along with the standard set of C and C++ dynamic memory allocation functions, the mpatrol library also comes with an additional set of functions which can be used to provide additional information to your program, and which can be called at various points in your code for debugging purposes. You must always include the '`mpatrol.h`' header file in order to use these functions, but you can check for a specific version of the mpatrol library by checking the `MPATROL_VERSION` preprocessor macro.

Certain mpatrol library options can be set after the library has been initialised with the `__mp_setoption()` function. This allows you to override the default options or those specified in the `MPATROL_OPTIONS` environment variable from within your code. Not all options can be overridden, however, since they would require a complete reinitialisation of the library — the

[7] Actually, it's not really the mpatrol library that uses the memory but the object file access libraries since they call `malloc()` to allocate any memory that they require.

[8] A set of tests that run without user intervention.

`__mp_setoption()` function returns a failure indicator in these cases. You can read the setting of any mpatrol library option with the corresponding function, `__mp_getoption()`.

It is possible to obtain a great deal of information about an existing memory allocation using the `__mp_info()` function. This takes an address as an argument and fills in any details about its corresponding memory allocation in a supplied structure. The following example illustrates this (it can be found in 'tests/pass/test4.c').

```
/*
 * Demonstrates and tests the facility for obtaining information
 * about the allocation a specific address belongs to.
 */


#include "mpatrol.h"
#include <stdio.h>


void display(void *p)
{
    __mp_allocstack *s;
    __mp_allocinfo d;
    __mp_symbolinfo i;

    if (!__mp_info(p, &d))
    {
        fprintf(stderr, "nothing known about address 0x%0*lX\n",
                sizeof(void *) * 2, p);
        return;
    }
    fprintf(stderr, "block:    0x%0*lX\n", sizeof(void *) * 2, d.block);
    fprintf(stderr, "size:     %lu\n", d.size);
    fprintf(stderr, "type:     %s\n", __mp_function(d.type));
    fprintf(stderr, "alloc:    %lu\n", d.alloc);
    fprintf(stderr, "realloc:  %lu\n", d.realloc);
    fprintf(stderr, "thread:   %lu\n", d.thread);
    fprintf(stderr, "event:    %lu\n", d.event);
    fprintf(stderr, "func:     %s\n", d.func ? d.func : "<unknown>");
    fprintf(stderr, "file:     %s\n", d.file ? d.file : "<unknown>");
    fprintf(stderr, "line:     %lu\n", d.line);
    for (s = d.stack; s != NULL; s = s->next)
    {
        fprintf(stderr, "\t0x%0*lX", sizeof(void *) * 2, s->addr);
        if (__mp_syminfo(s->addr, &i))
        {
            if (i.name != NULL)
                fprintf(stderr, " %s", i.name);
            if ((i.addr != NULL) && (i.addr != s->addr))
                fprintf(stderr, "%+ld",
                        (char *) s->addr - (char *) i.addr);
            if (i.object != NULL)
                fprintf(stderr, " [%s]", i.object);
        }
```

```
        else if (s->name != NULL)
            fprintf(stderr, " %s", s->name);
        fputc('\n', stderr);
    }
    fprintf(stderr, "typestr:  %s\n",
            d.typestr ? d.typestr : "<unknown>");
    fprintf(stderr, "typesize: %lu\n", d.typesize);
    fprintf(stderr, "userdata: 0x%0*lX\n", sizeof(void *) * 2, d.userdata);
    fprintf(stderr, "freed:    %d\n", d.freed);
}


void func2(void)
{
    void *p;

    if (p = malloc(16))
    {
        display(p);
        free(p);
    }
    display(p);
}


void func1(void)
{
    func2();
}


int main(void)
{
    func1();
    return EXIT_SUCCESS;
}
```

When this is compiled and run, it should give the following output, although the pointers are likely to be different.

```
block:    0x0806A0E8
size:     16
type:     malloc
alloc:    52
realloc:  0
thread:   0
event:    97
func:     func2
file:     test4.c
line:     84
          0x0804A743 func2+35 [./a.out]
          0x0804A790 func1+8 [./a.out]
          0x0804A79C main+8 [./a.out]
```

```
          0x4007C9CB __libc_start_main+255 [/lib/libc.so.6]
          0x0804A3E1 _start+33 [./a.out]
typestr:  <unknown>
typesize: 0
userdata: 0x00000000
freed:    0
nothing known about address 0x0806A0E8
```

As you can see, anything that the mpatrol library knows about any memory allocation can be obtained for use in your own code, which can be very useful if you need to write handlers to keep track of memory allocations, etc. for debugging purposes. It can also be useful to have this information when running your program within a debugger, so you can use the `__mp_printinfo()` function to display information about a heap address if your debugger supports calling functions from the command prompt. Note that the textual representation of the `type` field returned by the `__mp_info()` function can be obtained by calling `__mp_function()`.

The `userdata` field shown above can be set for any memory allocation with the `__mp_setuser()` function. This can have any value and is not interpreted by the mpatrol library. It was added for user code to associate its own data with memory allocations.

You may also have noticed the use of `__mp_syminfo()` in the above example. This function is very similar to the `__mp_info()` function except that instead of looking for the details of a memory allocation at a specific address, it looks for the details of a function symbol at that address. This provides user access to the data obtained by the mpatrol symbol handler, including line number information if the '`USEDEBUG`' option is supported and used.

It is also possible for you to be able to intercept calls to allocate, reallocate and deallocate memory for your own purposes. You can install prologue and epilogue functions that the mpatrol library will call before and after every time one of its functions is called. These can be used for additional tracing or simply to add extra checks to your code. The following code is an example of this and can be found in '`tests/pass/test2.c`'.

```
/*
 * Demonstrates and tests the facility for specifying user-defined
 * prologue and epilogue functions.
 */


#include "mpatrol.h"
#include <stdio.h>


typedef void (*prologue_handler)(MP_CONST void *, size_t, MP_CONST void *);
typedef void (*epilogue_handler)(MP_CONST void *, MP_CONST void *);


prologue_handler old_prologue;
epilogue_handler old_epilogue;


void prologue(MP_CONST void *p, size_t l, MP_CONST void *a)
{
    if (old_prologue != NULL)
        old_prologue(p, l, a);
    if (p == (void *) -1)
        fprintf(stderr, "allocating %lu bytes\n", l);
```

```
    else if (l == (size_t) -1)
        fprintf(stderr, "freeing allocation 0x%0*lX\n", sizeof(void *) * 2, p);
    else if (l == (size_t) -2)
        fprintf(stderr, "duplicating string ‘%s’\n", p);
    else
        fprintf(stderr, "reallocating allocation 0x%0*lX to %lu bytes\n",
                sizeof(void *) * 2, p, l);
}


void epilogue(MP_CONST void *p, MP_CONST void *a)
{
    if (p != (void *) -1)
        fprintf(stderr, "allocation returns 0x%0*lX\n", sizeof(void *) * 2, p);
    if (old_epilogue != NULL)
        old_epilogue(p, a);
}


int main(void)
{
    void *p, *q;

    old_prologue = __mp_prologue(prologue);
    old_epilogue = __mp_epilogue(epilogue);
    if (p = malloc(16))
        if (q = realloc(p, 32))
            free(q);
        else
            free(p);
    if (p = (char *) strdup("test"))
        free(p);
    __mp_prologue(old_prologue);
    __mp_epilogue(old_epilogue);
    return EXIT_SUCCESS;
}
```

Once again, if you compile and run the above code, you should see the following output.

```
allocating 16 bytes
allocation returns 0x0806A0E8
reallocating allocation 0x0806A0E8 to 32 bytes
allocation returns 0x0806A0E8
freeing allocation 0x0806A0E8
duplicating string ‘test’
allocation returns 0x0806A0E5
freeing allocation 0x0806A0E5
```

Note that in the above code, the previous prologue and epilogue functions were recorded and called. If this is not done then your prologue and epilogue functions will completely override all others, which is not usually the expected behaviour. In case you're wondering what the third argument of the prologue handler (and the second argument of the epilogue handler) is, it is the code address of the function that called `malloc()` or a related function. This can be used in the handlers to see where they were called from.

Along with being able to install prologue and epilogue functions, you can also install a low-memory handler with the `__mp_nomemory()` function, which will be called by the mpatrol library if it ever runs out of memory during the call to a memory allocation function. This gives you the opportunity to use that handler to either free up any unneeded memory or simply to abort, thus removing the need to check for failed allocations.

It is also possible to iterate over all of the allocated and freed memory allocations that are currently in the heap at any point in a program. This is done by invoking the `__mp_iterate()` function with a callback function which is called once per allocation with the start address of the memory block being passed as the argument to the callback function. Any further information about the memory allocation can then be obtained via the `__mp_info()` function.

Differences in the heap allocations (their details, not their contents) between a previous point in a program's execution and the current point of execution can be determined by calling the `__mp_snapshot()` function and then invoking `__mp_iterate()` with that snapshot value as its second argument at a later point in execution. The callback function passed to `__mp_iterate()` will then only be invoked with the start address of any memory allocation that has been allocated or reallocated (or freed if the '`NOFREE`' option is being used) since the snapshot point. This makes it possible to detect localised memory leaks very easily, as the following example (found in '`tests/pass/test10.c`') shows.

```
/*
 * Demonstrates and tests the facility for obtaining information on
 * local memory leaks.  Will also edit or list the location of each
 * leak if the EDIT or LIST option is in effect.
 */


#include "mpatrol.h"
#include <stdio.h>


int callback(MP_CONST void *p, void *t)
{
    __mp_allocstack *s;
    __mp_allocinfo d;

    if (!__mp_info(p, &d))
    {
        fprintf(stderr, "nothing known about address 0x%0*lX\n",
                sizeof(void *) * 2, p);
        return -1;
    }
    if (!d.freed)
    {
        fprintf(stderr, "0x%0*lX", sizeof(void *) * 2, d.block);
        fprintf(stderr, " %s", d.func ? d.func : "<unknown>");
        fprintf(stderr, " %s", d.file ? d.file : "<unknown>");
        fprintf(stderr, " %lu", d.line);
        for (s = d.stack; s != NULL; s = s->next)
        {
            if (s == d.stack)
                fputs(" (", stderr);
            else
                fputs("->", stderr);
```

```
            if (s->name != NULL)
                fprintf(stderr, "%s", s->name);
            else
                fprintf(stderr, "0x%0*lX", sizeof(void *) * 2, s->addr);
            if (s->next == NULL)
                fputc(')', stderr);
        }
        fputc('\n', stderr);
        if ((d.file != NULL) && (d.line != 0))
            __mp_view(d.file, d.line);
        *((unsigned long *) t) = *((unsigned long *) t) + d.size;
        return 1;
    }
    return 0;
}


void func2(unsigned long n)
{
    void *p;

    p = malloc((n * 10) + 1);
    if (n % 13)
        free(p);
}


void func1(void)
{
    void *p;
    size_t i, n;
    unsigned long s, t;

    p = malloc(16);
    s = __mp_snapshot();
    for (i = 0; i < 128; i++)
        func2(i);
    free(p);
    t = 0;
    if (n = __mp_iterate(callback, &t, s))
        fprintf(stderr, "Detected %lu memory leaks (%lu bytes)\n", n, t);
    if ((n != 10) || (t != 5860))
        fputs("Expected 10 memory leaks (5860 bytes)\n", stderr);
}


int main(void)
{
    void *p;

    p = malloc(16);
```

```
    func1();
    free(p);
    return EXIT_SUCCESS;
}
```

Compiling this example with mpatrol and then running it will produce the following list of memory leaks that were located between the points of calling `__mp_snapshot()` and `__mp_iterate()`.

```
0x0806A108 func2 test10.c 78 (func2->func1->main->_start)
0x0806A674 func2 test10.c 78 (func2->func1->main->_start)
0x0806A6F8 func2 test10.c 78 (func2->func1->main->_start)
0x0806A800 func2 test10.c 78 (func2->func1->main->_start)
0x0806A988 func2 test10.c 78 (func2->func1->main->_start)
0x0806AB94 func2 test10.c 78 (func2->func1->main->_start)
0x0806AE20 func2 test10.c 78 (func2->func1->main->_start)
0x0806B130 func2 test10.c 78 (func2->func1->main->_start)
0x0806B4C0 func2 test10.c 78 (func2->func1->main->_start)
0x0806B8D4 func2 test10.c 78 (func2->func1->main->_start)
Detected 10 memory leaks (5860 bytes)
```

The '`tools`' directory in the mpatrol distribution contains two files called '`heapdiff.c`' and '`heapdiff.h`' which demonstrate the use of `__mp_snapshot()` and `__mp_iterate()` to find localised memory leaks. Have a look at these files to see a further example of using these functions, or perhaps even add these files to your application for debugging purposes. Note that it is perfectly safe to allocate memory in the callback function used by `__mp_iterate()`, and such allocations can be freed as well. The only restriction is that the callback function should never free a memory allocation that it has not allocated itself.

If you wish to write your own diagnostics to the mpatrol log file from within your source code then you can do so with the `__mp_printf()` and `__mp_vprintf()` functions, which are the functional equivalents of `printf()` and `vprintf()`. They prefix every line written to the log file with '`>`', partly for making it clear where user diagnostics occur and partly to avoid problems with external utilities that parse the mpatrol log file. It is also possible to write out a memory dump in hexadecimal format, a stack trace at the current point in execution and details of a memory allocation to the log file in standard format using the `__mp_logmemory()`, `__mp_logstack()` and `__mp_logaddr()` functions respectively.

You can also take advantage of the `mpedit` command from within the mpatrol library with the `__mp_edit()`, `__mp_list()` and `__mp_view()` functions. The first invokes a text editor on a specified file and line number, while the second displays a context listing of a file at a given line number. The third function performs either or neither depending on the setting of the '`EDIT`' or '`LIST`' options.

Finally, there are four functions which affect the mpatrol library globally. The first, `__mp_check()`, allows you to force an internal check of the mpatrol library's data structures at any point during program execution and also to free up any out of scope memory allocations made by the `alloca()` family of functions. The `__mp_memorymap()` function allows you to force the generation of a memory map at any point in your program, in much the same way as it would normally be displayed at the end of program execution if the '`SHOWMAP`' option was used. The `__mp_summary()` function writes library statistics to the mpatrol log file, while the `__mp_stats()` function fills in a data structure with selected statistics for examination in user code.

7.8 Additional tools

The '`tools`' directory that comes with the mpatrol distribution contains the source code for tools that are built on top of the mpatrol library. The functions that are defined in these files are intended to be useful for specific applications as well as providing real-world examples of how to extend mpatrol. If you wish to use one of the source files in the '`tools`' directory then you should first compile it and then link it into your program along with the mpatrol library.

Alternatively, if you've already installed mpatrol on your system then there should be an '`mpatrol`' subdirectory within the include directory where '`mpatrol.h`' is installed that contains all of the header files in the '`tools`' directory. There should also be a libmptools library within the library directory where libmpatrol is installed that contains an object file for each of the source files in the '`tools`' directory. You can then make use of a particular tool by including its header file from the '`mpatrol`' include subdirectory and then linking with the libmptools library.

If you've written a useful extension to mpatrol then you might wish to submit it for inclusion in the next release of mpatrol. Even if it's just for a specific application, there might be other users out there that may benefit from it. You'll even get a credit in the manual! Note that any documentation should be written in the associated header file.

7.9 Utilities

Several external programs are supplied with the mpatrol distribution in the form of commands that can be used to enhance the functionality of the mpatrol library. Each command comes with its own UNIX manual page (although they also support the '`--help`' and '`--version`' options), but a few of the commands are written as UNIX shell scripts and so will not work on non-UNIX platforms. Note that the `mprof` command is documented in the profiling chapter (see Chapter 8 [Profiling], page 51) and the `mptrace` command is documented in the tracing chapter (see Chapter 9 [Tracing], page 63).

7.9.1 The `mpatrol` command

A command is provided with the mpatrol distribution which can run programs that have been linked with the mpatrol library, using a combination of mpatrol options that can be set via the command line. Most of these options map directly onto their equivalent environment variable settings and exist mainly so that the user does not have to manually change the `MPATROL_OPTIONS` environment variable.

The main option that is the exception to this is the '`--dynamic`' option, which can be used to run a program under the control of the mpatrol library, even if it wasn't originally linked with the mpatrol library. This can only be done on systems that support dynamic linking and where the dynamic linker recognises the `LD_PRELOAD` or `_RLD_LIST` environment variables. Even then, it can only be used when the program that is being run has been dynamically linked with the system C library, rather than statically linked.

The reason for all of these limitations is that some SVR4 UNIX platforms have a special feature in the dynamic linker which can be told to override the symbols from one shared library using the symbols from another shared library at run-time. In this case, it involves replacing the symbols for `malloc()`, etc., in the system C library with the mpatrol versions, but only if they were marked as undefined in the original executable file and would therefore have to have been loaded from '`libc.so`'.

However, if a program qualifies for use with the '`--dynamic`' option, it means that you can trace all of its dynamic memory allocations as well as running it with any of the mpatrol library's debugging options. This is mainly a *toy* feature which allows you to view and manipulate the dynamic memory allocations of programs that you don't have the source for, but in theory it could be quite useful if you need to debug a previously released executable and are unable to recompile or relink it. Note that if the program being run is multithreaded then you must add the '`--threads`' option as well.

Note that the `mpatrol` command must be set up to use the correct object file format access libraries that are required for your system if you wish to use the '`--dynamic`' option. If the mpatrol library was built with FORMAT=FORMAT_COFF or FORMAT=FORMAT_XCOFF support then it must be told to preload the COFF access library (normally 'libld.so'). If it was built with FORMAT=FORMAT_ELF32 or FORMAT=FORMAT_ELF64 support then it must be told to preload the ELF access library (normally 'libelf.so')[9]. If it was built with FORMAT=FORMAT_BFD support then it must be told to preload the GNU BFD access libraries (normally 'libbfd.so' and 'libiberty.so')[10]. However, if these libraries only exist on your system in archive form then you must build 'libmpatrol.so' with these extra libraries incorporated into it so that there are no dependencies on them at run-time. However, there may well be problems if the resulting shared library contains position-dependent code from the archive libraries you incorporated. The only way to find out is for you to try it and see.

If you have access to the GNU linker on your system then there may be a way to convert archive libraries into shared libraries if position-independent code is not necessarily required for building shared libraries on your system. If you use the '--whole-archive' and '--shared' linker options then the GNU linker will read the entire contents of one or more archive libraries before writing out a shared library. All going well, you should be able to use the new shared library in conjunction with the '--dynamic' mpatrol option.

In order to build a shared version of the mpatrol library with embedded object file format access libraries, you must first modify the 'Makefile' you would normally use to build the mpatrol library. At the lines where the linker is invoked to build the shared library, you must explicitly add any object file format access libraries that you want to use at the end of the linker command line. This ensures that all references to such libraries will be resolved at link time rather than run time. You must then edit the file 'src/config.h' and remove all of the libraries that you embedded from the definitions of the MP_PRELOAD_LIBS and 'MP_PRELOADMT_LIBS' preprocessor macros. Finally, rebuild the shared version of the mpatrol library and the mpatrol command and see if your efforts were worth it.

Because the mpatrol command sets the MPATROL_OPTIONS environment variable for each of the programs it runs, it does not affect the value of the environment variable for the current process (except on AmigaOS and Netware where all processes share the same environment). However, if you wish to use the mpatrol command to set MPATROL_OPTIONS in the current process environment then you can use its '--show-env' option to help you do so. This option will apply all of the mpatrol command line options to the MPATROL_OPTIONS environment variable and then display its value on the standard output without actually running any programs. You can then manually set the environment variable with the output from the mpatrol command.

If you wish the MPATROL_OPTIONS environment variable to be set in the current shell process automatically with the mpatrol command then you must use some shell trickery. The following script excerpts can be found in 'extra/.profile', 'extra/.cshrc' and 'extra/.gdbinit' and can be inserted into your ksh/bash, csh/tcsh and gdb configuration files respectively. They each provide the mallopt command, which takes mpatrol command options and sets the MPATROL_OPTIONS environment variable in the current shell or debugger process.

```
# mallopt for ksh/bash

function mallopt()
{
    export MPATROL_OPTIONS=‘mpatrol --show-env "$@"‘
    echo "$MPATROL_OPTIONS"
}

# mallopt for csh/tcsh
```

[9] A freely available version of the ELF access library, libelf, can be downloaded from ftp://sunsite.unc.edu/pub/Linux/libs/.

[10] The GNU BFD access library can be downloaded from ftp://ftp.gnu.org/.

```
alias mallopt 'setenv MPATROL_OPTIONS "`mpatrol --show-env \!*`";
               echo "$MPATROL_OPTIONS"'

# mallopt for gdb

define mallopt
printf "Enter mpatrol library options: "
shell read arg; echo set environment MPATROL_OPTIONS
               `mpatrol --show-env $arg` >/tmp/mpatrol.gdb
source /tmp/mpatrol.gdb
shell rm -f /tmp/mpatrol.gdb
show environment MPATROL_OPTIONS
end
document mallopt
Sets mpatrol library options in the current process environment.
end
```

7.9.2 The `mleak` command

Another utility program that is provided is called `mleak` and is useful for detecting memory leaks in log files produced by the mpatrol library. This program should be used if the mpatrol library could not finish writing the log file due to abnormal program termination (which would prevent the 'SHOWUNFREED' option from working), but note that some of the unfreed allocations might have been freed if the program had terminated successfully.

The `mleak` command scans through an mpatrol log file looking for lines beginning with 'ALLOC:' and 'FREE:' but ignores lines beginning with 'REALLOC:', so only the 'LOGALLOCS' and 'LOGFREES' options are necessary when running a program linked with the mpatrol library. Note that as a result of this, no attempt is made to account for resizing of memory allocations and so the total amount of memory used by the resulting unfreed allocations may not be entirely accurate.

This command will also read the unfreed allocations table produced by the 'SHOWUNFREED' option in the log file if one is present. The entries in the table will be compared with the currently allocated entries and will be added if not already present. However, this behaviour can be disabled by supplying the '`--ignore`' option to the `mleak` command.

The `mleak` command takes one optional argument which must be a valid mpatrol log filename but if it is omitted then it will use '`mpatrol.log`' as the name of the log file to use. The `mleak` command makes two passes over the log file so the file must be randomly-accessible. If the filename argument is given as '`-`' then the standard input file stream will be used as the log file. Note also that the `mleak` command supports the '`--help`' and '`--version`' options in common with the other mpatrol command line tools.

7.9.3 The `mpsym` command

Another utility program that is provided is called `mpsym`, which is used to parse a log file produced by the mpatrol library and uses a debugger to append symbol names and source level information to code addresses in stack tracebacks. This should be used if the 'USEDEBUG' option is not supported on a particular platform or does not work properly with a specific program. It will replace all existing symbols and source level information associated with the stack tracebacks in the mpatrol log file and will display the resulting log file on the standard output file stream.

The first argument to `mpsym` must be the filename of the executable file that produced the mpatrol log file but if it is omitted then `mpsym` will use '`a.out`' as the name of the executable file to use. The mpsym command will read the symbol table and debugging sections from this file in order to map the code addresses that appear in the mpatrol log file into symbol names and source level information. If the executable file does not contain a symbol table then no symbol names will be available and if it does not contain the appropriate debugging sections then no source level information will be available either. Obviously, if the executable file is not the same as the one that created the mpatrol log file then the final output will be wrong.

The second argument to mpsym must be a valid mpatrol log filename but if it is omitted then mpsym will use 'mpatrol.log' as the name of the log file to use. The mpsym command makes two passes over the log file so the file must be randomly-accessable. Note also that the mpsym command supports the '--help' and '--version' options in common with the other mpatrol command line tools.

The mpsym command currently uses gdb as the debugger with which to obtain the additional information about the code addresses in the mpatrol log file. It also makes use of several UNIX text processing commands, including perl if it is installed, in order to extract information from the debugger's output and from the log file. As a result, the mpsym command is only likely to work on UNIX platforms or on systems which have the necessary commands installed. By default, it is set up to work on 32-bit platforms, but this can be changed by altering the POINTER definition in the 'mpsym' file itself (this is only necessary if perl is not installed).

7.9.4 The mpedit command

Yet another utility program that is provided is called mpedit, which is used to invoke a text editor on a given source file and optionally jump to a specific line number. It is used as a support command by the mpatrol library when the 'EDIT' or 'LIST' options are used but it can quite easily be used as a command in its own right if properly configured. Because it is a shell script it can be easily configured to support other editors, but this unfortunately limits it to UNIX platforms at the moment.

The first argument to mpedit must be the filename of the source file to be edited or listed. If the source file does not exist then the contents of the MPATROL_SOURCEPATH environment variable will be used to help locate the source file, even if the filename contained an absolute or relative path component. This environment variable should consist of a colon-separated list of directory names which may contain absolute paths or be relative to the current directory; the first directory in the list will be searched first. If the MPATROL_SOURCEPATH environment variable is not set then only the current directory will be searched. You can also use the '--source-dir' option to add directories to the search path used to locate the source file. Multiple '--source-dir' options may be given, and each will be prepended to the MPATROL_SOURCEPATH environment variable in the order given on the command line.

If the second argument specifying the line number is omitted then it is assumed to be '1'. The text editor will attempt to jump to the specified line after opening the source file. The text editor that mpedit uses is controlled by setting the EDITOR environment variable. This can be set to the full pathname of the text editor to use or it can be set to the command that would normally be used to invoke the text editor, but it cannot also contain command line options. You can also use the '--editor' option to specify the text editor on the command line instead of using the value in the EDITOR environment variable.

The currently supported editors are vi, vim, emacs and xemacs, and if the EDITOR environment variable is not set then the default will be vi. Selecting an unsupported text editor will result in an error. However, you can edit the mpedit file to add support for your own favourite text editor as long as it supports a way to immediately jump to a specific line number when it is first started up. Note that the text editor must also open a new window to edit the source file so that it does not obscure any mpatrol diagnostic messages, and if it does not support this then a new terminal window must be opened for it to use.

If the '--listing' option is given on the command line then the mpedit command will display a context listing of the source file at the specified line number to the standard error output stream instead of invoking the text editor. The listing will be annotated with line numbers and will also show the contents of the five lines before and after the specified line if possible. Note also that the `mpedit` command supports the '`--help`' and '`--version`' options in common with the other mpatrol command line tools.

7.9.5 The `hexwords` command

The final utility program that is provided is called `hexwords`, which is used to generate hexadecimal constants from a dictionary of known words. Such numerical constants can be used in source files for a variety of debugging problems, and problems with uninitialised variables are especially relevant since these special numbers will stand out if seen from within a debugger. For example, here are some common (and some not-so-common) 32-bit hexadecimal constants that can be used as debugging aids:

word	*hex constant*
addedbad	`0xaddedbad`
allocate	`0xa110ca7e`
badlabel	`0xbad1abe1`
codebabe	`0xc0debabe`
deadbeef	`0xdeadbeef`
failsafe	`0xfa115afe`
feedface	`0xfeedface`
freedata	`0xf4eeda7a`

As can be seen above, many decimal digits can be used to represent the letters that they most closely resemble, along with the hexadecimal digits '`A`' through '`F`'. This provides a much larger selection of words that can be matched, although the digits '`3`' and '`8`' cannot be used due to the lack of any similar-looking letters. The digits and their corresponding letters are given in the following table.

digit	*letter*
'`0`'	O, o or Q
'`1`'	I, i or l
'`2`'	Z or z
'`3`'	-
'`4`'	q or R
'`5`'	S or s
'`6`'	G
'`7`'	J or T
'`8`'	-
'`9`'	g
'`A-F`'	A-F
'`a-f`'	a-f

The argument to `hexwords` must be a valid dictionary filename but if it is omitted then `hexwords` will use '`/usr/dict/words`' as the name of the dictionary file to use. If that cannot be found then hexwords will try '`/usr/lib/dict/words`' and '`/usr/share/dict/words`'. The dictionary file must be a plain text file that contains one word per line, otherwise few to no words will be matched.

The words that are matched from the dictionary file can be controlled by using the '`--match`' option, which sets the type of case-sensitivity to use. A setting of '`exact`' performs a case-sensitive comparison of all of the words in the dictionary file and the hexadecimal digits, whereas a setting of '`any`' does not. The '`lower`' and '`upper`' settings convert the words in the dictionary file to lower and upper case respectively before performing a case-sensitive comparison. The default case-sensitivity is '`exact`'.

The minimum and maximum number of letters that are matched are controlled by the '`--minimum`' and '`--maximum`' options. None of the hexadecimal numbers displayed will have any less or more digits that those specified with these options. The default minimum is '4' digits and the default maximum is '8' digits. Note also that the `hexwords` command supports the '`--help`' and '`--version`' options in common with the other mpatrol command line tools.

The `hexwords` command currently makes use of several UNIX text processing commands in order to extract the words and their hexadecimal equivalents. As a result, the `hexwords` command is only likely to work on UNIX platforms or on systems which have the necessary commands installed.

8 Profiling

The mpatrol library has the capability to summarise the information it accumulated about the behaviour of dynamic memory allocations and deallocations over the lifetime of any program that it was linked and run with. This summary shows a rough profile of all memory allocations that were made, and is hence called *profiling*. There are several other different kinds of profiling provided with most compilation tools, but they generally profile function calls or line numbers in combination with the time it takes to execute them.

Memory allocation profiling is useful since it allows a programmer to see which functions directly allocate memory from the heap, with a view to optimising the memory usage or performance of a program. It also summarises any unfreed memory allocations that were present at the end of program execution, some of which could be as a result of memory leaks. In addition, a summary of the sizes and distribution of all memory allocations and deallocations is available.

A memory allocation call graph is also available for the programmer to be able to see the caller and callee relationships for all functions that allocated memory, either directly or indirectly. This graph is shown in a tabular form similar to that of `gprof`, but it can also be written to a graph specification file for later processing by `dot`. The `dot` and `dotty` commands are part of GraphViz, an excellent graph visualisation package that was developed at AT&T Bell Labs and is available for free download for UNIX and Windows platforms from `http://www.research.att.com/sw/tools/graphviz/`.

Only allocations and deallocations are recorded, with each reallocation being treated as a deallocation immediately followed by an allocation. For full memory allocation profiling support, call stack traversal must be supported in the mpatrol library and all of the program's symbols must have been successfully read by the mpatrol library before the program was run. The library will attempt to compensate if either of these requirements are not met, but the displayed tables may contain less meaningful information. Cycles that appear in the allocation call graph are due to recursion and are currently dealt with by only recording the memory allocations once along the call stack.

Memory allocation profiling is disabled by default, but can be enabled using the '`PROF`' option. This writes all of the profiling data to a file called '`mpatrol.out`' in the current directory at the end of program execution, but the name of this file can be changed using the '`PROFFILE`' option and the default directory in which to place these files can be changed by setting the `PROFDIR` environment variable. Sometimes it can also be desirable for the mpatrol library to write out the accumulated profiling information in the middle of program execution rather than just at the end, even if it is only partially complete, and this behaviour can be controlled with the '`AUTOSAVE`' option. This can be particularly useful when running the program from within a debugger, when it is necessary to analyse the profiling information at a certain point during program execution.

Normally, the mpatrol library will perform profiling with all of its other features and checks enabled, but you might want to disable these if you only wish to profile the memory allocations. For example, you may wish to use the '`CHECK=0`' and '`NOPROTECT`' options to remove the internal checking of the library and speed up profiling dramatically.

When profiling memory allocations, it is necessary to distinguish between small, medium, large and extra large memory allocations that were made by a function. The boundaries which distinguish between these allocation sizes can be controlled via the '`SMALLBOUND`', '`MEDIUMBOUND`' and '`LARGEBOUND`' options, but they default to 32, 256 and 2048 bytes respectively, which should suffice for most circumstances.

The `mprof` command is a tool designed to read a profiling output file produced by the mpatrol library and display the profiling information that was obtained. The profiling information includes summaries of all of the memory allocations listed by size and the function that allocated them and a list of memory leaks with the call stack of the allocating function. It also includes a graph of all memory allocations listed in tabular form, and an optional graph specification file for later processing by the `dot` graph visualisation package.

The `mprof` command also attempts to calculate the endianness of the processor that produced the profiling output file and reads the file accordingly. This means that it is possible to use `mprof` on a SPARC machine to read a profiling output file that was produced on an Intel 80x86 machine, for example. However, this will only work if the processor that produced the profiling output file has the same word size as the processor that is running the `mprof` command. For example, reading a 64-bit profiling output file on a 32-bit machine will not work.

In addition, the profiling output file also contains the version number of the mpatrol library which produced it. If the major version number that is embedded in the profiling output file is newer that the version of mpatrol that `mprof` came with then `mprof` will refuse to read the file. You should download the latest version of mpatrol in that case. The reason for storing the version number is so that the format of the profiling output file can change between releases of mpatrol, but also allow `mprof` to cope with older versions.

Along with the options listed below, the `mprof` command takes one optional argument which must be a valid mpatrol profiling output filename but if it is omitted then it will use '`mpatrol.out`' as the name of the file to use. If the filename argument is given as '`-`' then the standard input file stream will be used as the profiling output file. Note also that the `mprof` command supports the '`--help`' and '`--version`' options in common with the other mpatrol command line tools.

'`--addresses`'
: Specifies that different call sites from within the same function are to be differentiated and that the names of all functions should be displayed with their call site offset in bytes. This affects the direct allocation and memory leak tables, as well as the allocation call graph and the graph specification file.

'`--counts`'
: Specifies that certain tables should be sorted by the number of allocations or deallocations rather than the total number of bytes allocated or deallocated. This affects the direct allocation and memory leak tables, as well as the allocation call graph and the graph specification file.

'`--graph-file`' <*file*>
: Specifies that the allocation call graph should also be written to a graph specification file for later visualisation with `dot`. If *file* is given as '`stdout`' or '`stderr`' then the corresponding file stream will be used as the target for the graph specification file.

'`--leaks`'
: Specifies that memory leaks rather than memory allocations are to be written to the graph specification file. This option only affects the output from the '`--graph-file`' option.

'`--stack-depth`' <*depth*>
: Specifies the maximum stack depth to use when calculating if one call site has the same call stack as another call site. This also specifies the maximum number of functions to display in a call stack. If *depth* is '`0`' then the call stack depth will be unlimited in size. The default call stack depth is '`1`'. This affects the memory leak table.

We'll now look at an example of using the mpatrol library to profile the dynamic memory allocations in a program. However, remember that this example will only fully work on your machine if the mpatrol library supports call stack traversal and reading symbols from executable files on that platform. If that is not the case then only some of the features will be available.

The following example program performs some simple calculations and displays a list of numbers on its standard output file stream, but it serves to illustrate all of the different features of memory allocation profiling that mpatrol is capable of. The source for the program can be found in '`tests/profile/test1.c`'.

```
/*
 * Associates an integer value with its negative string equivalent in a
 * structure, and then allocates 256 such pairs randomly, displays them
 * then frees them.
 */


#include <stdio.h>
#include <stdlib.h>
#include <string.h>


typedef struct pair
{
    int value;
    char *string;
}
pair;


pair *new_pair(int n)
{
    static char s[16];
    pair *p;

    if ((p = (pair *) malloc(sizeof(pair))) == NULL)
    {
        fputs("Out of memory\n", stderr);
        exit(EXIT_FAILURE);
    }
    p->value = n;
    sprintf(s, "%d", -n);
    if ((p->string = strdup(s)) == NULL)
    {
        fputs("Out of memory\n", stderr);
        exit(EXIT_FAILURE);
    }
    return p;
}


int main(void)
{
    pair *a[256];
    int i, n;

    for (i = 0; i < 256; i++)
    {
        n = (int) ((rand() * 256.0) / (RAND_MAX + 1.0)) - 128;
        a[i] = new_pair(n);
    }
```

```
    for (i = 0; i < 256; i++)
        printf("%3d: %4d -> \"%s\"\n", i, a[i]->value, a[i]->string);
    for (i = 0; i < 256; i++)
        free(a[i]);
    return EXIT_SUCCESS;
}
```

After the above program has been compiled and linked with the mpatrol library, it should be run with the '`PROF`' option set in the `MPATROL_OPTIONS` environment variable. Note that '`mpatrol.h`' was not included as it is not necessary for profiling purposes.

If all went well, a list of numbers should be displayed on the screen and a file called '`mpatrol.out`' should have been produced in the current directory. This is a binary file containing the total amount of profiling information that the mpatrol library gathered while the program was running, but it contains concise numerical data rather than human-readable data. To make use of this file, the `mprof` command must be run. An excerpt from the output produced when running `mprof` with no options is shown below.

```
                             ALLOCATION BINS

                          (number of bins: 1024)

                   allocated                           unfreed
        --------------------------------  --------------------------------
  size  count       %     bytes        %  count       %     bytes        %

     2      9    1.76        18     0.61      9    3.52        18     1.95
     3    105   20.51       315    10.61    105   41.02       315    34.16
     4    121   23.63       484    16.30    121   47.27       484    52.49
     5     21    4.10       105     3.54     21    8.20       105    11.39
     8    256   50.00      2048    68.96      0    0.00         0     0.00

 total    512              2970             256               922
                            DIRECT ALLOCATIONS

                 (0 < s <= 32 < m <= 256 < l <= 2048 < x)

        allocated                           unfreed
--------------------------  --------------------------
bytes        %   s  m  l  x bytes        %   s  m  l  x  count  function

 2970   100.00  %%             922   100.00  %%             512  new_pair

 2970           %%             922           %%             512  total
                              MEMORY LEAKS

                        (maximum stack depth: 1)

                   unfreed                          allocated
----------------------------------------  ----------------
     %    bytes        %   count       %     bytes   count  function

100.00      922    31.04     256   50.00      2970     512  new_pair
```

```
                         922   31.04     256   50.00      2970     512  total
                                    ALLOCATION CALL GRAPH

                                  (number of vertices: 3)

              allocated               unfreed
        ---------------------  ---------------------
index   bytes   s  m  l  x     bytes   s  m  l  x  function
-------------------------------------------------
[1]                                                 _start [1]
         2970  %%                922  %%                 main [3]
-------------------------------------------------
         2970  %%                922  %%                 main [3]
[2]                                                 new_pair [2]
-------------------------------------------------
         2970  %%                922  %%                 _start [1]
[3]                                                 main [3]
         2970  %%                922  %%                 new_pair [2]
```

The first table shown is the allocation bin table which summarises the sizes of all objects that were dynamically allocated throughout the lifetime of the program. In this particular case, counts of all allocations and deallocations of sizes 1 to 1023 bytes were recorded by the mpatrol library in their own specific *bin* and this information was written to the profiling output file. Allocations and deallocations of sizes larger than or equal to 1024 bytes are counted as well and the total number of bytes that they represent are also recorded. This information can be extremely useful in understanding which sizes of data structures are allocated most during program execution, and where changes might be made to make more efficient use of the dynamically allocated memory.

As can be seen from the allocation bin table, 9 allocations of 2 bytes, 105 allocations of 3 bytes, 121 allocations of 4 bytes, 21 allocations of 5 bytes and 256 allocations of 8 bytes were made during the execution of the program. However, all of these memory allocations except the 8 byte allocations were still not freed by the time the program terminated, resulting in a total memory leak of 922 bytes.

The next table shown is the direct allocation table which lists all of the functions that allocated memory and how much memory they allocated. The '`s m l x`' columns represent *small*, *medium*, *large* and *extra large* memory allocations, which in this case are 0 bytes is less than a small allocation, which is less than or equal to 32 bytes, which is less than a medium allocation, which is less than or equal to 256 bytes, which is less than a large allocation, which is less than or equal to 2048 bytes, which is less than an extra large allocation. The numbers listed under these columns represent a percentage of the overall total and are listed as '`%%`' if the percentage is 100% or as '`.`' if the percentage is less than 1%. Percentages of 0% are not displayed.

The information displayed in the direct allocation table is useful for seeing exactly which functions in a program directly perform memory allocation, and can quickly highlight where optimisations can be made or where functions might be making unnecessary allocations. In the example, this table shows us that 2970 bytes were allocated over 512 calls by `new_pair()` and that 922 bytes were left unfreed at program termination. All of the allocations that were made by `new_pair()` were between 1 and 32 bytes in size.

We could now choose to sort the direct allocation table by the number of calls to allocate memory, rather than the number of bytes allocated, with the '`--counts`' option to `mprof`, but that is not relevant in this example. However, we know that there are two calls to allocate memory from `new_pair()`, so we can use the '`--addresses`' option to `mprof` to show all call sites within functions rather than just the total for each function. This option does not affect the allocation bin table so the new output from `mprof` with the '`--addresses`' option looks like:

```
                          DIRECT ALLOCATIONS

               (0 < s <= 32 < m <= 256 < l <= 2048 < x)

       allocated                        unfreed
--------------------------  --------------------------
bytes       %   s  m  l  x  bytes       %   s  m  l  x  count  function

 2048   68.96  69                 0    0.00                256  new_pair+20
  922   31.04  31               922  100.00  %%            256  new_pair+140

 2970          %%               922          %%            512  total
                             MEMORY LEAKS

                       (maximum stack depth: 1)

                unfreed                      allocated
----------------------------------------  ----------------
     %     bytes       %   count       %     bytes   count  function

100.00       922  100.00     256  100.00       922     256  new_pair+140

             922   31.04     256   50.00      2970     512  total
                         ALLOCATION CALL GRAPH

                       (number of vertices: 4)

           allocated                unfreed
     ---------------------  ---------------------
index   bytes   s  m  l  x     bytes   s  m  l  x  function
-------------------------------------------------
[1]                                                _start+100 [1]
         2970  %%                922  %%               main+120 [4]
-------------------------------------------------
         2048  %%                  0                   main+120 [4]
[2]                                                new_pair+20 [2]
-------------------------------------------------
          922  %%                922  %%               main+120 [4]
[3]                                                new_pair+140 [3]
-------------------------------------------------
         2970  %%                922  %%               _start+100 [1]
[4]                                                main+120 [4]
         2048  %%                  0                   new_pair+20 [2]
          922  %%                922  %%               new_pair+140 [3]
```

The names of the functions displayed in the above tables now have a byte offset appended to them to indicate at what position in the function a call to allocate memory occurred[1]. Now

[1] If no symbols could be read from the program's executable file, or if the corresponding symbol could not be determined, then the function names will be replaced with the code addresses at which the calls took place.

it is possible to see that the first call to allocate memory from within `new_pair()` has had all of its memory freed, but the second call (from `strdup()`) has had none of its memory freed.

This is also visible in the next table, which is the memory leak table and lists all of the functions that allocated memory but did not free all of their memory during the lifetime of the program. The default behaviour of `mprof` is to show only the function that directly allocated the memory in the memory leak table, but this can be changed with the '`--stack-depth`' option. This accepts an argument specifying the maximum number of functions to display in one call stack, with zero indicating that all functions in a call stack should be displayed. This can be useful for tracing down the functions that were indirectly responsible for the memory leak. The new memory leak table displayed by `mprof` with the '`--addresses`' and '`--stack-depth 0`' options looks like:

```
                              MEMORY LEAKS

                        (maximum stack depth: 0)

                  unfreed                          allocated
  ----------------------------------------  ----------------
        %      bytes         %     count         %      bytes    count   function

   100.00        922    100.00       256    100.00        922      256   new_pair+140
                                                                           main+120
                                                                           _start+100

                 922     31.04       256     50.00       2970      512   total
```

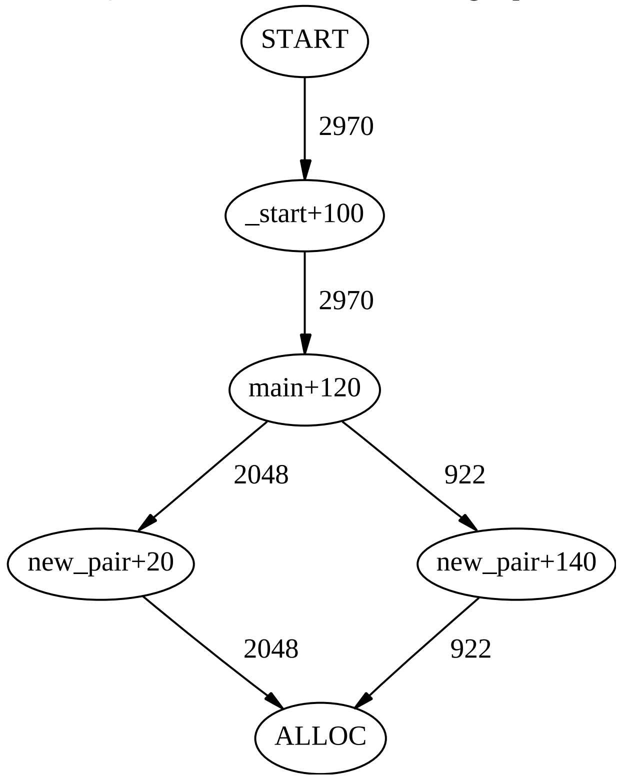
Now that we know where the memory leak is coming from, we can fix it by freeing the string as well as the structure at line 77. A version of the above program that does not contain the memory leak can be found in '`tests/profile/test2.c`'.

The final table that is displayed is the allocation call graph, which shows the relationship between a particular function in the call graph, the functions that called it (parents), and the functions that it called (children). Every function that appears in the allocation call graph is displayed with a particular index that can be used to cross-reference it. The functions which called a particular function are displayed directly above it, while the functions that the function called are displayed directly below it. In the above example, `_start()` called `main()`, which then called `new_pair()` which allocated the memory.

The memory that has been allocated by a function (either directly, or indirectly by its children) for its parents is shown in the details for the parent functions, showing both a breakdown of the allocated memory and a breakdown of the unfreed memory. This also occurs for the child functions. If a function does not directly allocate memory then the total memory allocated for its parents will equal the total memory allocated by its children. However, if a parent or child function is part of a cycle in the call graph then a '`(*)`' will appear in the leftmost column of the call graph. In that case the total incoming memory may not necessarily equal the total outgoing memory for the main function.

In the example above when the '`--addresses`' option is used, it should be clear that `new_pair()+20` allocates 2048 bytes for `main()`, while `new_pair()+140` allocates 922 bytes for `main()`. The `main()` function itself allocates 2970 bytes for `_start()` overall via the `new_pair()` function.

It is also possible to view this information graphically if you have the GraphViz package mentioned above installed on your system. The '`--graph-file`' option can be used to write a `dot` graph specification file that can be processed by the `dot` or `dotty` commands that come with GraphViz. The resulting graphs will show the relationships between each function, its parents and its children, and will also show the number of bytes that were allocated along the edges of the call graph, but this can be changed to the number of calls if the '`--counts`' option is used[2]. A call graph showing unfreed memory instead of allocated memory can be generated by adding the '`--leaks`' option. The following graph illustrates the use of these options with the above example. It was generated using the '`--addresses`' and '`--graph-file`' options.



As a final demonstration of mpatrol's profiling features we will attempt to profile a real application in order to see where the memory allocations come from. Since all of the following steps were performed on a Solaris machine, the '`--dynamic`' option of the `mpatrol` command was used to allow us to replace the system memory allocation routines with mpatrol's routines without requiring a relink. It also means that we can profile all of the child processes that were created by the application as well.

The application that we are going to profile is the GNU C compiler, `gcc` (version 2.95.2), which is quite a complicated and large program. The actual `gcc` command is really the compiler driver which invokes the C preprocessor followed by the compiler, the assembler, the prelinker and finally the linker (well, it does in this example). On Solaris, the `gcc` distribution uses the system assembler and linker which come with no symbol tables in their executable files so we will not be profiling them.

For the purpose of this demonstration we will only be looking at the graph files produced by the '`--graph-file`' option of the `mprof` command, but ordinarily you would want to look at the tables that `mprof` produces as well. All of the command line examples use the `bash` shell but in most cases these will work in other shells with a minimal amount of changes.

We will use '`tests/profile/test2.c`' as the source file to compile with `gcc` and we'll turn on optimisation in order to cause `gcc` to allocate a bit more memory than it would normally. Note that use is also made of the format string feature of the '`--log-file`' and '`--prof-file`' options so that it is clear which mpatrol log and profiling output files belong to which processes.

```
bash$ mpatrol --dynamic --log-file=%p.log --prof-file=%p.out
              --prof gcc -O -o test2 test2.c
```

[2] Cycles in the graph are marked by dashed lines along the relevant edges instead of solid lines.

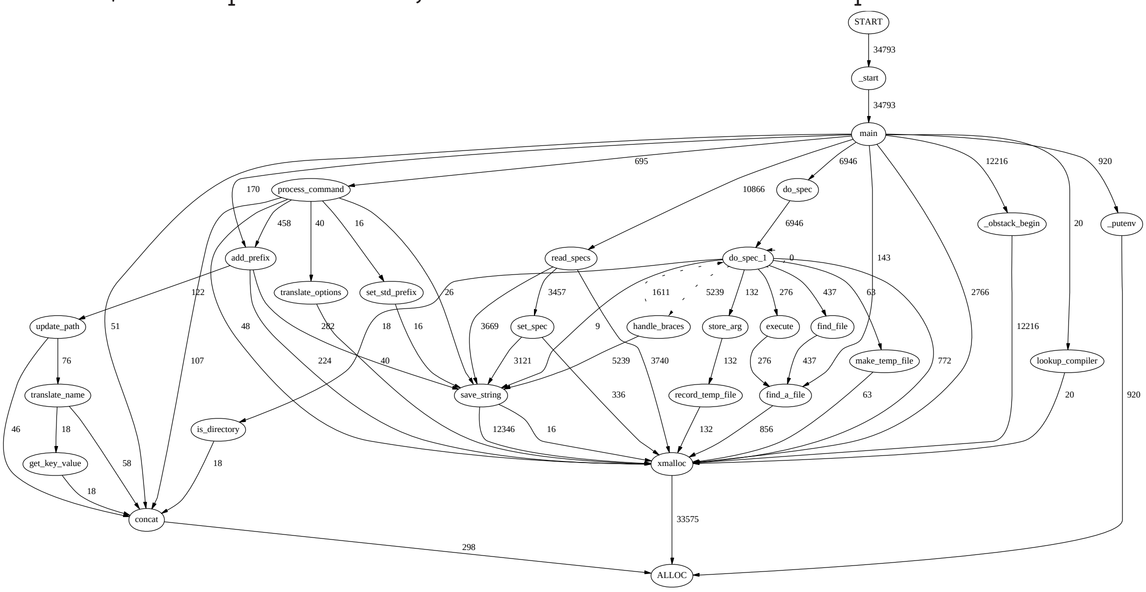
```
bash$ ls *.log *.out
as.log          cc1.out         cpp.log         gcc.out
as.out          collect2.log    cpp.out         ld.log
cc1.log         collect2.out    gcc.log         ld.out
```

As mentioned above, we're not interested in the mpatrol log and profiling output files for `as` and `ld` so we'll delete them. We can now use `mprof` to create graph specification files for each of the profiling output files produced. You can find these graph specification files and the profiling output files used to generate them in the '`extra`' directory in the mpatrol distribution.

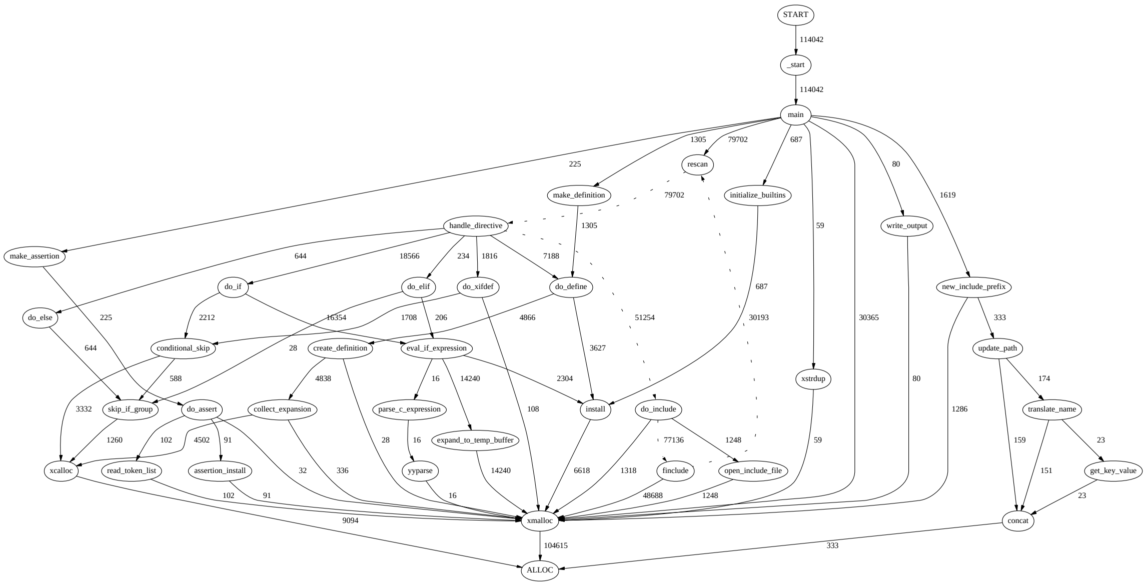
```
bash$ rm as.log as.out ld.log ld.out
bash$ ls *.out
cc1.out         collect2.out    cpp.out         gcc.out
bash$ for file in *.out
> do
>     mprof --graph-file=`basename $file .out`.dot $file
> done >/dev/null
bash$ ls *.dot
cc1.dot         collect2.dot    cpp.dot         gcc.dot
```

The graph specification files that have now been produced can be viewed and manipulated with the `dotty` command, or they can be converted to various image formats with the `dot` command. However, this presumes that you already have the GraphViz graph visualisation package installed. If you have then you can convert the graph specification files to GIF and postscript images using the following commands. If not, you can still view the graphs produced in the following figures.

```
bash$ dot -Tgif -Gsize="6,3" -Gratio=fill -o gcc.gif gcc.dot
bash$ dot -Tgif -Gsize="6,3" -Gratio=fill -o cpp.gif cpp.dot
bash$ dot -Tgif -Gsize="7,4" -Gratio=fill -o cc1.gif cc1.dot
bash$ dot -Tgif -Gsize="4,3" -Gratio=fill -o collect2.gif collect2.dot
bash$ dot -Tps -Gsize="6,3" -Gratio=fill -o gcc.ps gcc.dot
bash$ dot -Tps -Gsize="6,3" -Gratio=fill -o cpp.ps cpp.dot
bash$ dot -Tps -Gsize="9,6" -Gratio=fill -Grotate=90 -o cc1.ps cc1.dot
bash$ dot -Tps -Gsize="4,3" -Gratio=fill -o collect2.ps collect2.dot
```



The figure above shows the allocation call graph for the `gcc` compiler driver. From the graph you can see that the vast majority of memory allocations appear to be required for reading the driver specification file, which details default options and platform-specific features. Almost all of the memory allocations go through the `xmalloc()` routine, which is an error-checking function built on top of `malloc()`[3]. A large amount of memory is also allocated by the *obstack* module, which provides a functionality similar to *arenas* for variable-sized data structures. You'll see extensive use of both of these types of routines throughout the following graphs.



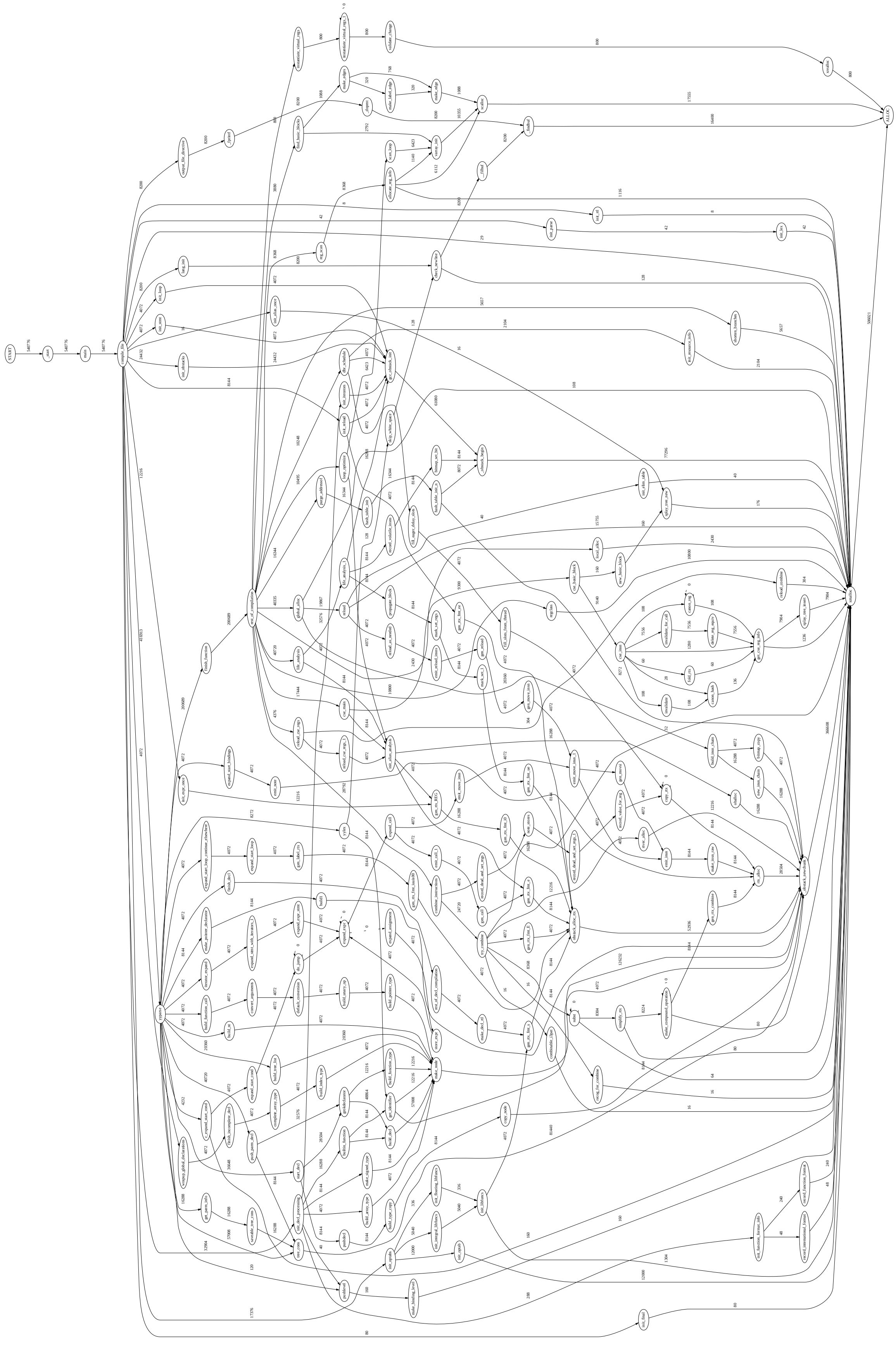
As would be expected, in the above allocation call graph for the `cpp` C preprocessor, the majority of memory allocations are used for macro processing, with a sizable chunk being allocated for reading include files. You may also notice the dotted lines that connect the `rescan()`, `handle_directive()`, `do_include()` and `finclude()` functions[4]. These show a cycle in the call graph where each of these functions may have been involved in one or more recursive calls. The labels for such dotted edges may not be entirely accurate since `mprof` will only count allocated memory once for each recursive call chain.

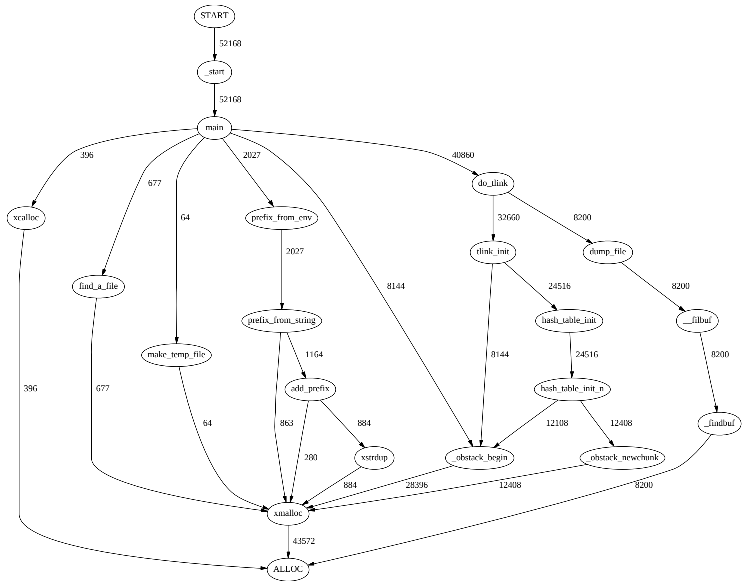
The following figure shows the allocation call graph for the `cc1` compiler itself. As you would expect, it's a bit of a beast compared to the previous two graphs, and looks very hard to follow. However, if you look closer you will notice that the various groups of functions that comprise the compiler stand out due to their close association with one another. For example, you might notice that the functions between `cse_insn()` and `get_cse_reg_info()` form a group that allocates 9140 bytes overall. You can also see the parser module at the top left of the graph, initiated with `yyparse()`, and the code generator module in the rest of the graph, initiated with `rest_of_compilation()`.

---

[3] The mpatrol version of `xmalloc()` was not used in this case since another version of `xmalloc()` was originally statically linked into the program being run, and so could not be overridden.

[4] You might also have noticed the dotted lines connecting `do_spec_1()` and `handle_braces()` in the previous graph.





The allocation call graph for the prelinker, `collect2`, is a lot simpler than the previous graphs. There are no cycles in the graph and most of the allocations are concerned with maintaining hash tables. Once again, `xmalloc()` and `_obstack_begin()` are the two main sources of memory allocation.

As can be seen, a lot of information about the memory allocation behaviour of a program can be obtained by creating a visual image of the allocation call graph. In addition, different graphs can be produced to show call counts instead of allocated bytes (via the '`--counts`' option), and graphs of unfreed memory can be produced to detect where memory leaks come from (via the '`--leaks`' option).

Much of the functionality of this implementation of memory allocation profiling is based upon `mprof` by Benjamin Zorn and Paul Hilfinger, which was written as a research project and ran on MIPS, SPARC and VAX machines. However, the profiling output files are incompatible, the tables displayed have a different format, and the way they are implemented is entirely different.

9 Tracing

In addition to profiling, the mpatrol library also has the capability to concisely trace the details of every dynamic memory allocation and deallocation over the lifetime of any program that it was linked and run with. This information can then be used to calculate trends in a program's memory allocation behaviour and provide details on the lifetimes of memory allocations. In contrast to profiling, it can also be used to display a program's memory allocation behaviour in real-time, along with some useful information that can be displayed in graphical or tabular form.

As with profiling, only allocations and deallocations are recorded, with each reallocation being treated as a deallocation immediately followed by an allocation. The intention of tracing is to gather concise details about each memory allocation event rather than complete information about some or all memory allocations. As a result, the mpatrol log files and profiling output files contain more detailed information about individual memory allocations, whereas the tracing output files contain a broader view of allocation behaviour throughout the entire program.

Memory allocation tracing is disabled by default, but can be enabled using the '`TRACE`' option. This writes all of the tracing data to a file called '`mpatrol.trace`' in the current directory at the end of program execution, but the name of this file can be changed using the '`TRACEFILE`' option and the default directory in which to place these files can be changed by setting the `TRACEDIR` environment variable.

Normally, the mpatrol library will perform tracing with all of its other features and checks enabled, but you might want to disable these if you only wish to trace the memory allocations. For example, you may wish to use the '`CHECK=0`' and '`NOPROTECT`' options to remove the internal checking of the library and speed up tracing dramatically.

The `mptrace` command is a tool designed to read a tracing output file produced by the mpatrol library and display the tracing information that was obtained. The tracing information is a concise encoded trace of all of the memory allocation events that occurred during a program's execution, and can be decoded into tabular or graphical form, along with any relevant statistics that can be calculated.

The `mptrace` command also attempts to calculate the endianness of the processor that produced the tracing output file and reads the file accordingly. This means that it is possible to use `mptrace` on a SPARC machine to read a tracing output file that was produced on an Intel 80x86 machine, for example. However, this will only work if the processor that produced the tracing output file has the same word size as the processor that is running the `mptrace` command. For example, reading a 64-bit tracing output file on a 32-bit machine will not work.

In addition, the tracing output file also contains the version number of the mpatrol library which produced it. If the major version number that is embedded in the tracing output file is newer that the version of mpatrol that `mptrace` came with then `mptrace` will refuse to read the file. You should download the latest version of mpatrol in that case. The reason for storing the version number is so that the format of the tracing output file can change between releases of mpatrol, but also allow `mptrace` to cope with older versions.

Along with the usual '`--help`' and '`--version`' options, the `mptrace` command takes one optional argument which must be a valid mpatrol tracing output filename but if it is omitted then it will use '`mpatrol.trace`' as the name of the file to use. If the filename argument is given as '`-`' then the standard input file stream will be used as the tracing output file.

The `mptrace` command will normally be built with GUI[1] support on UNIX platforms that are running X Windows. This means that a graphical memory map display of the heap will be shown in a window every time `mptrace` is run. This display is updated every time a new event is read from the tracing output file and by default uses the colour red for internal heap memory (used by the mpatrol library), blue for unallocated heap memory, black for allocated

[1] Graphical User Interface.

memory and white for free memory. Options exist to change this colour scheme, as well as the dimensions of the drawing area and the window.

By default, it is assumed that the start address of the first event that appears in the tracing output file is the base address of the memory map displayed in the window. If the heap grows downwards then this assumption will be incorrect (since nothing will be displayed) and so the '`--base`' option must be used to specify a reasonable lower bound for the final memory map. In addition, the visible address space displayed in the memory map is fixed to a certain size (4 megabytes by default), but this can be changed with the '`--space`' option. A small delay can also be added after drawing each memory allocation event through the use of the '`--delay`' option.

The following options are specific to the GUI version of `mptrace` and are read by the X command line parser rather than directly by `mptrace`. As a result they are parsed according to X toolkit rules and do not appear in the quick-reference option summary produced by the '`--help`' option. The application class for setting `mptrace` X resources is called '`MPTrace`'.

'`--alloc`' <*colour*>
: Specifies the colour to use for displaying allocated memory. The default colour is '`black`'.

'`--base`' <*address*>
: Specifies the base address of the visible address space displayed in the memory map. The default address is calculated at run-time from the start address of the first memory allocation event in the tracing output file.

'`--delay`' <*length*>
: Specifies that a small delay of a certain length should be added after drawing each memory allocation event. The delay does not correspond to a specific unit of time, but experimentation with the length should yield satisfactory results. The default delay is '`0`'.

'`--free`' <*colour*>
: Specifies the colour to use for displaying free memory. The default colour is '`white`'.

'`--height`' <*size*>
: Specifies the height (in pixels) of the drawing area. The default height is '`512`'.

'`--internal`' <*colour*>
: Specifies the colour to use for displaying internal heap memory. The default colour is '`red`'.

'`--space`' <*size*>
: Specifies the size (in megabytes) of the visible address space displayed in the memory map. The default size is '`4`'.

'`--unalloc`' <*colour*>
: Specifies the colour to use for displaying unallocated heap memory. The default colour is '`blue`'.

'`--view-height`' <*size*>
: Specifies the height (in pixels) of the window. The default height is '`256`'.

'`--view-width`' <*size*>
: Specifies the width (in pixels) of the window. The default width is '`256`'.

'`--width`' <*size*>
: Specifies the width (in pixels) of the drawing area. The default width is '`512`'.

We'll now look at an example of using the mpatrol library to trace the dynamic memory allocations in a program. As with the previous chapter we will attempt to trace a real application in order to examine its memory allocation behaviour. Since all of the following steps were performed on a Solaris machine, the '--dynamic' option of the mpatrol command was used to allow us to replace the system memory allocation routines with mpatrol's routines without requiring a relink. It also means that we can trace all of the child processes that were created by the application as well.

The application that we are going to trace is the GNU C compiler, as before, and we will discard the tracing information generated for the assembler and linker. All of the command line examples use the bash shell but in most cases these will work in other shells with a minimal amount of changes.

We will use 'tests/profile/test2.c' as the source file to compile with gcc and we'll turn on optimisation in order to cause gcc to allocate a bit more memory than it would normally. Note that use is also made of the format string feature of the '--log-file' and '--trace-file' options so that it is clear which mpatrol log and tracing output files belong to which processes.

```
bash$ mpatrol --dynamic --log-file=%p.log --trace-file=%p.trace
              --trace gcc -O -o test2 test2.c
bash$ ls *.log *.trace
as.log         cc1.trace      cpp.log        gcc.trace
as.trace       collect2.log   cpp.trace      ld.log
cc1.log        collect2.trace gcc.log        ld.trace
```

As mentioned above, we're not interested in the mpatrol log and tracing output files for as and ld so we'll delete them. We can now use mptrace to decode each of the tracing output files produced and write their contents in tabular form to the standard output file stream, which can be redirected to a file for later viewing[2]. You can find these tracing output files in the 'extra' directory in the mpatrol distribution.

```
bash$ rm as.log as.trace ld.log ld.trace
bash$ ls *.trace
cc1.trace      collect2.trace cpp.trace      gcc.trace
bash$ for file in *.trace
> do
>     mptrace $file >`basename $file .trace`.res
> done
bash$ ls *.res
cc1.res        collect2.res   cpp.res        gcc.res
```

For the purposes of this example we will only be looking at the tracing results for the cc1 compiler which are now decoded in the file 'cc1.res'. If you examine this file you will see something similar to the following. Note that the '...' marks text that has been removed.

```
 event  type     index  allocation      size    life
------  ------  ------  ----------  --------  ------
        internal        0x0024E000     32768
        internal        0x00256000     32768
        internal        0x0025E000     32768
        reserve         0x00266000      8192
        internal        0x00268000     32768
        internal        0x00270000     32768
        internal        0x00278000     32768
        internal        0x00280000     32768
        internal        0x00288000     32768
        internal        0x00290000     32768
...
        reserve         0x00308000     16384
```

[2] If you are running a GUI version of mptrace you will need to close the window after each file has been decoded.

```
      1  alloc       19  0x00266568      4072
      2  alloc       21  0x0030A008      4072
      3  alloc       22  0x0030AFF0      4072
         reserve         0x0030C000      8192
      4  alloc       23  0x0030BFD8      4072
      5  alloc       24  0x0030CFC0      4072
         reserve         0x0030E000      8192
      6  alloc       25  0x0030DFA8      4072
      7  alloc       26  0x00267550        42
...
   1712  free       650  0x00373FF0      4072       827
   1713  free       649  0x00376FA8      4072       829
   1714  alloc     1074  0x00376FA8      4072
   1715  free       233  0x0031ED18      8200      1498
   1716  free       234  0x00320D20      8200      1498
   1717  free       299  0x00355CC8       620      1426
   1718  free       655  0x00353A28      1016       823
   1719  free       303  0x0035E000      5096      1424
   1720  free       653  0x00354E60       152       827
   1721  free       654  0x00354EF8       152       827
```

There are six different columns of data displayed by the `mptrace` command when it decodes the tracing output file and displays it in tabular format. Here is an explanation for each of them.

‘`event`’
: This contains the event number (or time line) for each memory allocation or deallocation (heap reservations are not considered events for this purpose). Each memory allocation or deallocation increases the current event number, and this information is used to calculate the lifetime of a heap allocation.

‘`type`’
: This contains the event type for each entry in the tracing output file. Memory allocations and deallocations are represented by ‘`alloc`’ and ‘`free`’ respectively. Normal heap reservations (that will be used for memory allocations) are represented by ‘`reserve`’, while internal heap reservations (for use by the mpatrol library itself) are represented by ‘`internal`’.

‘`index`’
: This contains the allocation index that is used by the mpatrol library to keep track of each unique memory allocation, and corresponds directly to any memory allocations listed in the log file. Any memory allocation events that reuse allocation indices represent a reallocation of the original allocation.

‘`allocation`’
: This contains the start address of the memory allocation.

‘`size`’
: This contains the size (in bytes) of the memory allocation.

‘`life`’
: This contains the lifetime of a memory allocation and is displayed when it is is freed. It is simply the difference between the current event number and the event number at which the original allocation took place, but is useful for working out how long a memory allocation is valid throughout a program’s execution. If a memory allocation is reallocated, its lifetime will be calculated from the original time of allocation, *not* the point at which it was reallocated.

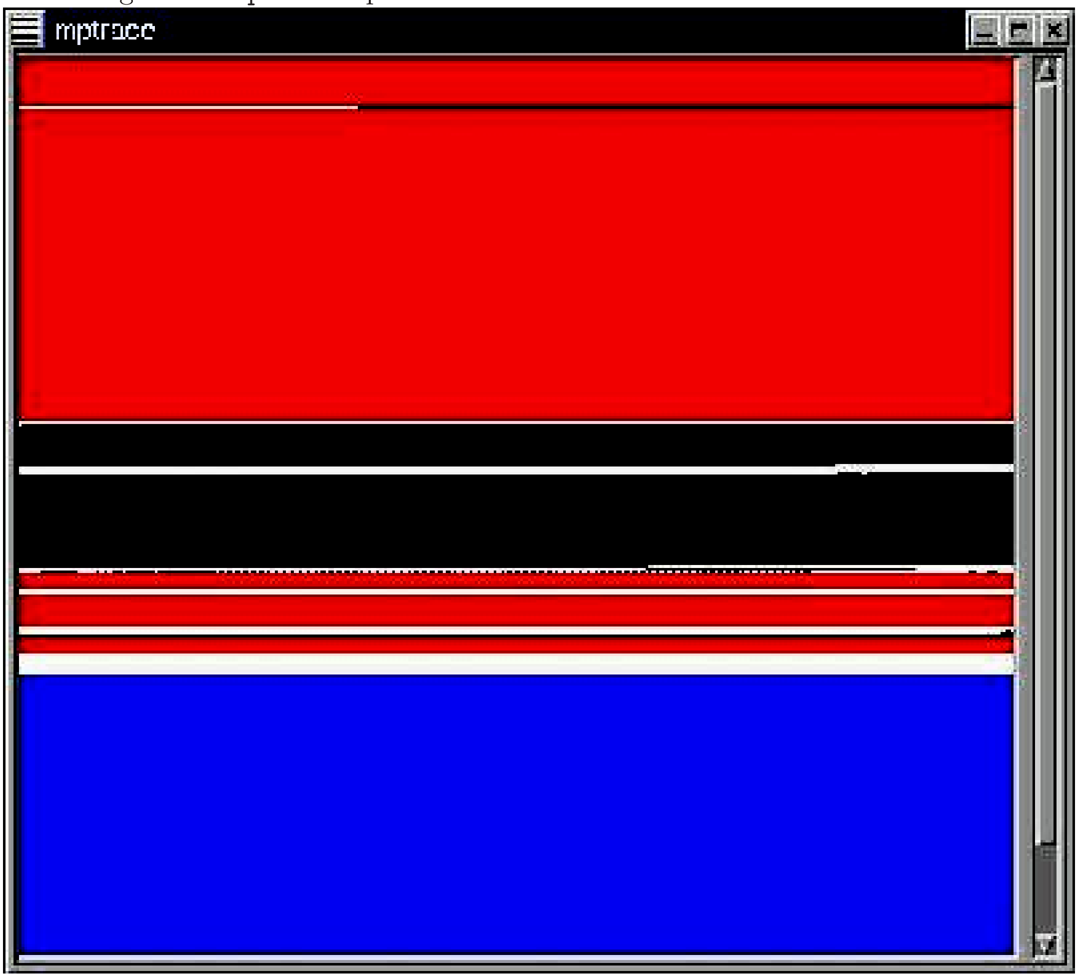
The first few entries in the table show that the mpatrol library started by allocating memory from the heap for its own purposes before reserving 8192 bytes for the memory allocations made by the object file access library for reading the symbols from the executable file and shared libraries[3]. Most of the further internal heap reservation events are due to the mpatrol library

[3] The actual allocation events from this do not appear since they were internal memory allocations.

having to store details for all of the relevant symbols that it could read at program startup. The more symbols that there are, the more memory that must be used to store them. Note that the heap reservation events are not really relevant to the analysis of the program's memory allocations but they are used when displaying the heap graphically.

The first few memory allocation events in the table show that several memory allocations of 4072 bytes are being made along with several more heap reservations that are needed to store them. The last events in the table are mainly all deallocation events of allocations that were made quite early on in the program. The lifetime information for these events shows that some of these allocations were made very near the beginning of the program, while the others were made near the middle. None of them were very big and so would not be occupying much memory.

As you will have noticed if you were running a GUI version of `mptrace`, information about all of these events is displayed in graphical form inside the `mptrace` display window. The following screenshot shows the `mptrace` display window when it is run with '`cc1.trace`' as input. It was generated using the '`--space 2`' option.



Areas coloured blue indicate heap memory that has not yet been used by the mpatrol library (i.e. it has not currently been allocated from the system, or is currently being used by a part of the program that is not being tracked by the mpatrol library). Areas coloured red indicated heap memory that is being used internally by the mpatrol library. In this example, the reason that there is so much internal memory being used is that there are a large number of symbols that were read from the executable file and shared libraries. The narrow band of black and white lines at the top of the memory map represents the memory that was used by the object file access library when it was reading the symbols.

The large black bands in the middle of the memory map indicate memory that was still allocated at program termination. While this is a substantial amount compared to the amount of free memory, it does not necessary indicate memory leaks as the memory could be being used right up until the end of the program, and is implicitly freed at program termination anyway.

Unlike memory allocation profiling which summarises all of the accumulated data, it is possible to trace memory allocation events in real-time as the program runs. This can currently be done on UNIX platforms by piping the tracing output file from the program being run to the `mptrace` command, which can be achieved in several ways depending on the UNIX system that you are using. Both of the following methods are equivalent, where '`testprog`' is the name of the program that is being traced (and has previously been linked with the mpatrol library).

```
# This method specifies the standard output file stream as the
# destination for the tracing output file and then runs both
# commands in a shell command pipe.  This has a disadvantage in
# that testprog must not write anything to stdout since that would
# be written out to the tracing output file.  If stdout is not
# suitable then stderr could be used instead if you redirect it.

bash$ mpatrol --trace-file=stdout --trace ./testprog | mptrace -
```

```
# This method creates a named pipe called myfifo (but it could be
# called anything) and runs the program being traced and the mptrace
# command separately (perhaps in two separate windows).  If the
# mkfifo command is not available on your system then try mknod.

bash$ mkfifo myfifo
bash$ mpatrol --trace-file=myfifo --trace ./testprog &
bash$ mptrace myfifo
```

The idea for graphically displaying a memory map of the heap comes from the `xmem` tool supplied with the University of Toronto Computer Systems Research Institute malloc library, written by Mark Moraes. However, the documentation for that tool remarks that it was written as a quick and dirty hack. The `mptrace` command is hopefully more stable and contains a lot more functionality.

The mpatrol library can also generate trace files in a format that is compatible with the GNU `mtrace()` option. The code to do this is built on top of the mpatrol library and is in '`tools/mtrace.c`' and '`tools/mtrace.h`'. Such trace files can then be processed by the GNU `mtrace` command. The '`tools/mgauge.c`' and '`tools/mgauge.h`' files in the same directory can be used to implement an allocated memory gauge which updates in real-time in a terminal window. This can be used as an alternative to the window used by the `mptrace` command for a simpler display.

10 Improving performance

Because of their need to cover every eventuality, malloc library implementations are very general and most do their job well when you consider what is thrown at them. However, your program may not be performing as well as it should simply because there may be a more efficient way of dealing with dynamic memory allocations. Indeed, there may even be a more efficient malloc library available for you to use.

If you need to allocate lots of blocks of the same size[1], but you won't know the number of blocks you'll require until run-time then you could take the easy approach by simply allocating a new block of memory for each occurrence. However, this is going to create a lot of (typically small) memory blocks that the underlying malloc library will have to keep track of, and even in many good malloc libraries this is likely to cause memory fragmentation and possibly even result in the blocks scattered throughout the address space rather than all in the one place, which is not necessarily a good thing on systems with virtual memory.

An alternative approach would be to allocate memory in multiples of the block size, so that several blocks would be allocated at once. This would require slightly more work on your part since you would need to write interface code to return a single block, while possible allocating space for more blocks if no free blocks were available. However, this approach has several advantages. The first is that the malloc library only needs to keep track of a few large allocations rather than lots of small allocations, so splitting and merging free blocks is less likely to occur. Secondly, your blocks will be scattered about less in the address space of the process, which means that on systems with virtual memory there are less likely to be page faults if you need to access or traverse all of the blocks you have created.

A memory allocation concept that is similar to this is called an *arena*. This datatype requires functions which are built on top of the existing malloc library functions and which associate each memory allocation with a particular arena. An arena can have as many allocations added to it as required, but allocations cannot usually be freed until the whole arena is freed. Note that there are not really any generic implementations of arenas that are available as everyone tends to write their own version when they require it, although Digital UNIX and SGI IRIX systems do come with an arena library called *amalloc*.

However, what if you don't plan to free all of the blocks at the same time? A slight modification to the above design could be to have a *slot table*. This would involve allocating chunks of blocks as they are required, adding each individual block within a chunk to a singly-linked list of free blocks. Then, as new blocks are required, the allocator would simply choose the first block on the free list, otherwise it would allocate memory for a new chunk of blocks and add them to the free list. Freeing individual blocks would simply involve returning the block to the free list. If this description isn't clear enough, have a look in '`src/slots.h`' and '`src/slots.c`'. This is how the mpatrol library allocates memory from the system for all of its internal structures. For variable-sized structures, a slightly different approach needs to be taken, but for an example of this using strings see '`src/strtab.h`' and '`src/strtab.c`'.

Another optimisation that is possible on UNIX and Windows platforms is making use of memory-mapped files. This allows you to map a filesystem object into the address space of your process, thus allowing you to treat a file as an array of bytes. Because it uses the virtual memory system to map the file, any changes you make to the mapped memory will be applied to the file. This is implemented through the virtual memory system treating the file as a pseudo swap file and will therefore only use up physical memory when pages are accessed. It also means that file operations can be replaced by memory read and write operations, leading to a very fast and efficient way of performing I/O. Another added bonus of this system means that entire blocks of process memory can be written to a file for later re-use, just as long as the file can later be mapped to the same address. This can be a lot faster than writing to and reading from a specific format of file.

[1] Such as for use in a linked list.

If you really don't want to keep track of dynamic memory allocations at all then perhaps you should consider *garbage collection*. This allows you to make dynamic memory allocations that need not necessarily be matched by corresponding calls to free these allocations. A garbage collector will (at certain points during program execution) attempt to look for memory allocations that are no longer referenced by the program and free them for later re-use, hence removing all possibility of memory leaks. However, the garbage collection process can take a sizable chunk of processor time depending on how large the program is, so it is not really an option for real-time programming. It is also very platform-dependent as it examines very low-level structures within a process in order to determine which pointers point to which memory allocations. But there is at least one garbage collector[2] that works well with C and C++ and acts as a replacement for `malloc()` and `free()`, so it may be the ideal solution for you.

If you do choose to use an alternative malloc library make sure that you have a license to do so and that you follow any distribution requirements. On systems that support dynamic linking you may want to link the library statically rather than dynamically so that you don't have to worry about an additional file that would need to be installed. However, whether you have that choice depends on the license for the specific library, and some licenses also require that the source code for the library be made readily available. Shared libraries have the advantage that they can be updated with bug fixes so that all programs that require these libraries will automatically receive these fixes without needing to be relinked.

If all of the above suggestions do not seem to help and you still feel that you have a performance bottleneck in the part of your code that deals with dynamically allocated memory then you should try using the memory allocation profiling feature of mpatrol. This can be used at run-time to analyse the dynamic memory allocation calls that your program makes during its execution, and builds statistics for later viewing with the `mprof` command. It is then possible for you to see exactly how many calls were made to each function and where they came from. Such information can then be put to good use in order to optimise the relevant parts of your code. The tracing output files that can be produced by the mpatrol library may also be useful in order to view patterns in memory allocation behaviour and gather information about lifetimes of memory allocations.

And finally, some tips on how to correctly use dynamic memory allocations. The first, most basic rule is to *always* check the return values from `malloc()` and related functions. *Never* assume that a call to `malloc()` will succeed, because you're unlikely to be able to read the future[3]. Alternatively, use (or write) an `xmalloc()` or similar function[4], which calls `malloc()` but never returns '`NULL`' since it will abort instead. With the C++ operators it is slightly different because some versions use exceptions to indicate failure, so you should always provide a handler to deal with this eventuality.

Never use *features*[5] of specific malloc libraries if you want your code to be portable. Always follow the ANSI C or C++ calling conventions and never make assumptions about the function or operator you are about to call — the standards committees went to great lengths to explicitly specify its behaviour. For example, don't assume that the contents of a freed memory allocation will remain valid until the next call to `malloc()`, and don't assume that the contents of a newly allocated memory block will be zeroed unless you created it with `calloc()`.

Try to avoid allocating arrays on the stack if they are to hold data that may overflow. In most cases this is common sense, but sometimes you may allocate an array that should suffice for 99% of the time. However, if there is a 1% chance that it may overflow then on some systems the stack is executable and hackers can use that *feature* to break into a secure program by overwriting the current function's return address on the stack. Use statically-allocated or dynamically-allocated arrays for these situations, or better still, check for overflow.

---

[2] A freely distributably library called GC (see Appendix J [Related software], page 181).

[3] If you can, why are you reading this — you've already read it!

[4] The mpatrol library comes with the `xmalloc()` and `MP_MALLOC()` families of functions.

[5] Whether they are documented or not.

Finally, try stress-testing your program in low memory conditions. The mpatrol library contains the 'LIMIT' option which can place an upper bound on the size of the heap, and also contains the 'FAILFREQ' and 'FAILSEED' options which can cause random memory allocation failures. Doing this will test parts of your code that you would probably never expect to be called, but perhaps they will one day! Who would you rather have debugging your program — yourself or the user?

11 How it works

The mpatrol library was originally written with the intention of plugging it into an existing compiler so that the compiler could plant calls to it in the code it generated when a specific debugging option was used. These extra calls would obviously slow the code down, but along with the stack checking options that would be provided, this would give the user an enhanced run-time debugging environment. Unfortunately, this integration never happened, but the way that mpatrol works is still significantly different from other malloc tracing libraries.

In order to quickly determine exactly which memory allocation a heap address belonged to it was necessary to be able to search the heap in an efficient manner. The traditional way of searching along a linked list was unfeasible, so an implementation based on *red-black trees* was used, where every known memory allocation in the heap was given an entry in the tree, with their start addresses as the key. Another major design decision was to also choose red-black trees to implement the *best fit* allocation algorithm. Although *first fit* was considered, I decided that best fit would allow the library to have more control over the heap, with every free memory block in the heap given an entry in the free tree, with their sizes as the key. There was a bit of work involved in getting the splitting and merging of free blocks to work efficiently, but it seems to work well now.

My original implementation had all of the information about each memory block stored just before the block itself. I eventually dropped that behaviour in favour of storing all of the library's internal information in a separate part of the heap. I did that for two reasons. The first was because of the problems that would occur due to memory allocations with different alignment requirements. The second reason was that the library's internal structures could be write-protected on systems with virtual memory, to prevent user code interfering with the operation of the library.

Because the library attempts to record as much information as possible about every memory allocation there will inevitably be a much larger memory requirement when running a program linked with the library. This will typically be two or three times larger in magnitude, but will be affected by the number of memory allocations made and also the number of symbols read. The latter will also affect how quickly the program starts since the first call to allocate memory will result in the initialisation of the library and the loading of symbols from the executable file and any shared libraries.

Due to its design, it is also possible to allocate memory from the heap using the mpatrol library functions whilst already within an mpatrol library function. This does not normally occur, but on some platforms calling `printf()` from within the library may result in `printf()` calling `malloc()` to allocate itself a buffer, which ends up as a recursive call. Luckily, this is dealt with by simply not displaying the allocation in the log file, but all other details of the allocation are still recorded. This can sometimes result in *hidden* memory usage which occurs behind the scenes and alters the peak memory usage in the summary. This is particularly evident when the library uses an object file access library to read program symbols at the time of library initialisation.

Memory allocation profiling support was added for mpatrol release 1.2.0. Every allocation and deallocation is recorded, with the call stack information being used to differentiate all of the call sites within the program. Unlike other profilers that come with UNIX systems, even the symbolic information about the program being run is written to the profiling output file, since it makes no sense for `mprof` to re-read the symbol table from the executable file when it has already been read and processed by the mpatrol library. It also has the added bonus of allowing the user to save profiling output files for later use even when the executable files which produced them have changed or no longer exist.

Memory allocation tracing support was added for mpatrol release 1.3.2 and was added to produce concise information for every memory allocation event. This information could also be produced in a verbose form in the log file, but to log every memory allocation event in a large program would result in a massive log file that would be hard to parse. In order to keep the size of the tracing output file down, almost all of the data in the file is encoded as LEB128 numbers. The idea for this comes from the DWARF 2 debugging format.

Support for the `alloca()` family of functions was added for mpatrol release 1.3.0 and uses the heap instead of the stack in order to trace and debug these functions. If full call stack tracebacks are supported on a particular system then mpatrol will compare the current call stack with the call stack of the function that called `alloca()` in order to determine if a memory allocation made by `alloca()` is out of scope. This is generally a safe way to determine when such allocations should be freed, but if full call stack tracebacks are not supported then mpatrol will compare the addresses of specific local variables in the call stack in order to determine if the allocation should be freed. This is an inferior method since it depends on the same function call sequence being used each time an mpatrol function is called. Therefore, a safety boundary was added that will prevent mpatrol from freeing such allocations unless they are a really clear-cut case (i.e. the stack frames differ by a minimum number of bytes). As a result, this second method will not usually free such allocations until a much later point.

The library is written in a modular fashion so as to make it easy to add new functionality. New modules have already been added, such as the *stack*, *symbol*, *profile* and *trace* modules. Extra information about each memory allocation can be added to the *allocation information* module in '`src/info.h`' and '`src/info.c`' without having to change much code in any other files.

The '`tools`' directory in the mpatrol distribution comes with a collection of functions that are built on top of the mpatrol library using its interface functions. This provides a way to extend the mpatrol library for specific applications without requiring that all applications use the extensions. It also provides a way to add new interfaces to the library, perhaps for compatibility with other malloc debugging libraries.

Platform-dependent code has been isolated to specific modules, and feature macros are entirely defined and controlled from '`config.h`' and '`target.h`'. The source code has been written so as to make it as easy as possible to compile the library on new platforms at the first attempt, although any additional features that the platform supports will then have to be explicitly enabled in the code.

Of the UNIX platforms that the mpatrol library runs on, Solaris and Linux proved to be the easiest to port to, with well documented and easily accessible programming interfaces to operating system features. Unfortunately, the non-UNIX ports proved a lot harder to write and do not contain as many of the useful features that the UNIX ports have, although sometimes not because they cannot ever support them, but because there would be a huge amount of work involved.

12 Examples

Following are a set of examples that are intended to illustrate what exactly is possible with the mpatrol library and how to go about using it effectively.

You should already have built and installed the library and should know how to link programs with the library. Unfortunately, it isn't possible to give specific instructions on how to do this as it varies from system to system and also depends on your preferred compiler and development tools.

However, on a typical SVR4 UNIX system, with mpatrol installed in '/usr/local', the mpatrol library can usually be incorporated into a program using the following commands:

- If the mpatrol library was built with no support for any object file format or was built with support for the 'a.out' object file format:
  ```
  cc -I/usr/local/include <file> -L/usr/local/lib -lmpatrol
  ```
- If the mpatrol library was built with support for the COFF or XCOFF object file format access library (not on LynxOS systems):
  ```
  cc -I/usr/local/include <file> -L/usr/local/lib -lmpatrol -lld
  ```
- If the mpatrol library was built with support for the ELF32 or ELF64 object file format access library:
  ```
  cc -I/usr/local/include <file> -L/usr/local/lib -lmpatrol -lelf
  ```
- If the mpatrol library was built with support for the GNU BFD object file format access library:
  ```
  cc -I/usr/local/include <file> -L/usr/local/lib -lmpatrol -lbfd
     -liberty
  ```
- If the mpatrol library was built on HP/UX with support for the GNU BFD object file format access library:
  ```
  cc -I/usr/local/include <file> -L/usr/local/lib -lmpatrol -lbfd
     -liberty -lcl
  ```

On Windows platforms, with mpatrol installed in '/mpatrol', the mpatrol library can usually be incorporated into a program using the following commands:

- If the program is to be linked with the archive version of the mpatrol library:
  ```
  cl -I/mpatrol/include -Zi <file> -link -libpath:/mpatrol/lib
     -defaultlib:libmpatrol -defaultlib:imagehlp -pdb:none
  ```
- If the program is to be linked with the DLL version of the mpatrol library:
  ```
  cl -I/mpatrol/include -MD -Zi <file> -link -libpath:/mpatrol/lib
     -defaultlib:mpatrol -pdb:none
  ```

If you need to link with other libraries, make sure that they don't contain definitions of `malloc()`, etc., or if they do then you must ensure that the mpatrol library appears before them on the link line. Note also that if the mpatrol library was built on IRIX with the `MP_LIBRARYSTACK_SUPPORT` preprocessor macro defined, then the 'libexc' library must be linked in as well. You should also check the section on supported systems (see Appendix G [Supported systems], page 155) to see if there are any other issues on the platform that you are using.

You should also know how to set an environment variable on your specific system. Again, this varies from system to system and also depends on the command line interpreter or shell that you use. The environment variable that the mpatrol library uses is called `MPATROL_OPTIONS`. You can see exactly what options are available for this environment variable by setting it to 'HELP' and then running a program that has been linked with the library.

12.1 Getting started

The first example we'll look at is when the argument in a call to `free()` doesn't match the return value from `malloc()`, even though the intention is to free the memory that was allocated by `malloc()`. This example is in '`tests/fail/test1.c`' and causes many existing `malloc()` implementations to crash.

Along the way, I'll try to describe as many features of the mpatrol library as possible, and illustrate them with examples. Note that the output from your version of the library is likely to vary slightly from that shown in the examples, especially on non-UNIX systems.

```
23  /*
24   * Allocates a block of 16 bytes and then attempts to free the
25   * memory returned at an offset of 1 byte into the block.
26   */


29  #include "mpatrol.h"


32  int main(void)
33  {
34      char *p;

36      if (p = (char *) malloc(16))
37          free(p + 1);
38      return EXIT_SUCCESS;
39  }
```

Note that I've removed the copyright message from the start of the file and added line numbers so that the tracing below makes more sense.

After compiling and linking the above program with the mpatrol library, the `MPATROL_OPTIONS` environment variable should be set to be '`LOGALL`' and the program should be executed, generating the following output in '`mpatrol.log`'.

```
@(#) mpatrol 1.4.0 (01/02/21)
Copyright (C) 1997-2001 Graeme S. Roy

This is free software, and you are welcome to redistribute it under
certain conditions; see the GNU Library General Public License for
details.

For the latest mpatrol release and documentation,
visit http://www.cbmamiga.demon.co.uk/mpatrol.

Log file generated on Wed Feb 21 21:56:05 2001

read 310 symbols from /usr/lib/libmpatrol.so.1.4
read 647 symbols from /usr/lib/libbfd-2.9.5.0.22.so
read 2634 symbols from /lib/libc.so.6
read 1142 symbols from /usr/lib/libstdc++-libc6.1-1.so.2
read 695 symbols from /lib/libm.so.6
read 178 symbols from /lib/ld-linux.so.2
read 158 symbols from ./test1
```

```
ALLOC: malloc (52, 16 bytes, 4 bytes) [main|test1.c|36]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

returns 0x080620E8

FREE: free (0x080620E9) [main|test1.c|37]
        0x08049457 main+71
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

ERROR: [MISMAT]: free: 0x080620E9 does not match allocation of 0x080620E8
    0x080620E8 (16 bytes) {malloc:52:0} [main|test1.c|36]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

system page size:  4096 bytes
default alignment: 4 bytes
overflow size:     0 bytes
overflow byte:     0xAA
allocation byte:   0xFF
free byte:         0x55
allocation stop:   0
reallocation stop: 0
free stop:         0
unfreed abort:     0
small boundary:    32 bytes
medium boundary:   256 bytes
large boundary:    2048 bytes
lower check range: 0
upper check range: 0
check frequency:   1
failure frequency: 0
failure seed:      972951591
prologue function: <unset>
epilogue function: <unset>
handler function:  <unset>
log file:          mpatrol.log
profiling file:    mpatrol.out
tracing file:      mpatrol.trace
program filename:  ./test1
symbols read:      5764
autosave count:    0
freed queue size:  0
allocation count:  52
allocation peak:   20 (427512 bytes)
allocation limit:  0 bytes
allocated blocks:  7 (1528 bytes)
freed blocks:      0 (0 bytes)
```

```
free blocks:       4 (432648 bytes)
internal blocks:   33 (540672 bytes)
total heap usage:  974848 bytes
total compared:    0 bytes
total located:     2 bytes
total copied:      32176 bytes
total set:         582856 bytes
total warnings:    0
total errors:      1
```

Ignoring the copyright blurb at the top, let's first take a look at the initial log message from the library. I've annotated each of the items with a number that corresponds to the descriptions below.

```
 (1)    (2)   (3)    (4)       (5)     (6)    (7)  (8)
  |      |     |      |         |       |      |    |
  V      V     V      V         V       V      V    V
ALLOC: malloc (52, 16 bytes, 4 bytes) [main|test1.c|36]
 (9) -> 0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33 <- (10)

returns 0x080620E8 <- (11)
```

1. Allocation type. This generalises the type of dynamic memory operation that is being performed, and can be one of '`ALLOC`', '`REALLOC`' or '`FREE`'. This should make looking for all allocations, reallocations or frees in the log file a lot easier. Alternatively, if a memory operation function was called then this can also be one of '`MEMSET`', '`MEMCOPY`', '`MEMFIND`' or '`MEMCMP`'.
2. Allocation function. This is the name of the function that has been called to allocate the memory, in this case '`malloc`'.
3. Allocation index. This is incremented every time a new memory allocation is requested, and persists even if the memory allocation is resized with `realloc()` and its related functions, so can be useful to keep track of a memory allocation, even if its start address changes. The mpatrol library may use up the first few allocation indices when it gets initialised.
4. Size of requested allocation.
5. Alignment for requested allocation. This is normally the default system alignment for general-purpose memory allocations, but may be different depending on the type of function that is used to allocate the memory.

The following information contains source file details of where the call to `malloc()` came from, but is only available if the source file containing the call to `malloc()` included '`mpatrol.h`'; otherwise the fields will all be '`-`'[1]. Because of the convoluted way this information is obtained for the C++ operators, you may encounter some problems in existing C++ programs when making direct calls to `operator new` for example. However, if you want to disable the redefinition of the C++ operators in '`mpatrol.h`' you can define the preprocessor macro `MP_NOCPLUSPLUS` before the inclusion of that file. Alternatively, you may wish to define the `MP_NONEWDELETE` preprocessor macro in order to use `MP_NEW`, `MP_NEW_NOTHROW` and `MP_DELETE` instead of `new` and `delete`. That way you can combine calls to mpatrol's operators and the standard operators. Just make sure you don't mix them!

If you are running on a system on which mpatrol supports full symbolic stack tracebacks the following information may still be useful if the source files were compiled with optimisation

[1] This information may also be filled in if the '`USEDEBUG`' option or the `mpsym` command is used and supported, and if debugging information about the call to `malloc()` is available.

turned on. This is because the calling function may have been inlined, in which case you will only see the name of the function into which the calling function was expanded in the stack traceback.

6. Function where call to `malloc()` took place. This information is only available if the source file containing the call to `malloc()` was compiled with `gcc` or `g++`.
7. Filename in which call to `malloc()` took place.
8. Line number at which call to `malloc()` took place.

The following information contains function call stack details of where the call to `malloc()` came from, but is only available if the mpatrol library has been built on a platform that supports this. The top-most entry should be the function which called `malloc()` and the bottom-most entry should be the entry-point for the process.

9. Address of function call. This is normally the address of the machine instruction immediately after the function call instruction, also known as the return address.
10. Function where call took place. This information is only available if the mpatrol library has been built on a platform that supports reading symbol table information from executable files, and then only if there is an entry in the symbol table corresponding to the return address. C++ function names may still be in their mangled form, but this can be easily rectified by processing the log file with a C++ name demangler. The number after the plus sign is the offset in bytes from the beginning of the function.

The following information is only available when the allocation type is '`ALLOC`' or '`REALLOC`' since it makes no sense when applied to '`FREE`'.

11. The address of the new memory block that has been allocated by `malloc()`.

As you can see, there is quite a lot of information that can be displayed from a simple call to `malloc()`, and hopefully this information has been presented in a clear and concise format in the log file.

The next entries in the log file correspond to the call to `free()`, which attempts to free the memory allocated by `malloc()`, but supplies the wrong address.

The first four lines should be self-explanatory as they are very similar to those described above for `malloc()`. However, the next lines signal that a terminal error has occurred in the program, so I've annotated them as before.

```
FREE: free (0x080620E9) [main|test1.c|37]
        0x08049457 main+71
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

 (1)     (2)      (3)
  |       |        |
  V       V        V
ERROR: [MISMAT]: free: 0x080620E9 does not match allocation of 0x080620E8
       (4)        (5)        (6)  (7)(8)  (9)    (10) (11)
        |          |          |    |  |    |       |    |
        V          V          V    V  V    V       V    V
    0x080620E8 (16 bytes) {malloc:52:0} [main|test1.c|36]
(12) -> 0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33
```

1. Error severity. The mpatrol library has two different severities of error: '`WARNING`' and '`ERROR`'. The first is always recoverable, and serves only to indicate that something is not

quite right, and so may be useful in determining where something started to go wrong. The second may or may not be recoverable, and the library terminates the program if it is fatal, displaying any relevant information as it does this.

2. Error abbreviation code. This is a code that is different for each type of error that is detected by the mpatrol library. Some warnings and errors that are not directly related to the program being run will not contain this field. See the appendix on diagnostic messages (see Appendix D [Diagnostic messages], page 143) for a complete list of all possible error abbreviation codes and their descriptions.
3. Allocation function. This is the name of the function used to allocate, reallocate or free memory where the error was detected. This may be omitted if an error is detected elsewhere in the library.

The following information is related to the information that the library has stored about the relevant memory allocation. This information is always displayed in this format when details of individual memory allocations are required. If any information is missing then it simply means that the library was not able to determine it when the memory block was first allocated.

4. Address of memory allocation.
5. Size of memory allocation.
6. Allocation function. This is the name of the function that was called to allocate the memory block, in this case '`malloc`'. If the memory allocation has been resized then this will be either '`realloc`', '`reallocf`', '`recalloc`', '`expand`' or '`xrealloc`'.
7. Allocation index.
8. Reallocation index. This is used to count the number of times a memory allocation has been resized with `realloc()` and its related functions.
9. Function where original call to `malloc()` took place. If the memory allocation has been resized then this will be the name of the function which last called `realloc()` and its related functions.
10. Filename in which original call to `malloc()` took place. If the memory allocation has been resized then this will be the filename in which the last call to `realloc()` and its related functions took place.
11. Line number at which original call to `malloc()` took place. If the memory allocation has been resized then this will be the line number at which the last call to `realloc()` and its related functions took place.
12. Function call stack of original memory allocation. If the memory allocation has been resized then this will be the call stack of the last call to `realloc()` and related functions.

So, the mpatrol library detected the error in the above program and terminated it. When the library terminates it always displays a summary of various memory allocation statistics and settings that were used during the execution of the program.

The various settings and statistics displayed by the library for the above example have been numbered and their descriptions appear below.

```
 1  system page size:  4096 bytes
 2  default alignment: 4 bytes
 3  overflow size:     0 bytes
 4  overflow byte:     0xAA
 5  allocation byte:   0xFF
 6  free byte:         0x55
 7  allocation stop:   0
 8  reallocation stop: 0
 9  free stop:         0
10  unfreed abort:     0
```

```
11  small boundary:    32 bytes
12  medium boundary:   256 bytes
13  large boundary:    2048 bytes
14  lower check range: 0
15  upper check range: 0
16  check frequency:   1
17  failure frequency: 0
18  failure seed:      972951591
19  prologue function: <unset>
20  epilogue function: <unset>
21  handler function:  <unset>
22  log file:          mpatrol.log
23  profiling file:    mpatrol.out
24  tracing file:      mpatrol.trace
25  program filename:  ./test1
26  symbols read:      5764
27  autosave count:    0
28  freed queue size:  0
29  allocation count:  52
30  allocation peak:   20 (427512 bytes)
31  allocation limit:  0 bytes
32  allocated blocks:  7 (1528 bytes)
33  freed blocks:      0 (0 bytes)
34  free blocks:       4 (432648 bytes)
35  internal blocks:   33 (540672 bytes)
36  total heap usage:  974848 bytes
37  total compared:    0 bytes
38  total located:     2 bytes
39  total copied:      32176 bytes
40  total set:         582856 bytes
41  total warnings:    0
42  total errors:      1
```

1. System page size. This value is used on some platforms when allocating and protecting system memory.
2. Default alignment. This value is the minimum alignment required for general purpose memory allocations, and is usually the alignment required by the most restrictive datatype on a given system. It is used when allocating memory that has no specified alignment. It can be changed at run-time using the '`DEFALIGN`' option, but setting this value too small may cause the program to crash due to bus errors which are caused by reading from or writing to misaligned data.
3. Overflow size. This value is the size used by one overflow buffer. If this is non-zero then every memory allocation will have two overflow buffers; one on either side. These buffers are used by the library to detect if the program has written too many bytes to a memory allocation, thus overflowing into one of the buffers, but these extra checks can slow down execution speed. It can be changed at run-time using the '`OFLOWSIZE`' option.
4. Overflow byte.
5. Allocation byte.
6. Free byte. These values are used by the library to pre-fill blocks of memory for checking purposes. The overflow byte is used to fill overflow buffers, the allocation byte is used to fill newly-allocated memory (except from `calloc()` or `recalloc()`), and the free byte is used

to fill free blocks or freed memory allocations. These can be changed at run-time using the 'OFLOWBYTE', 'ALLOCBYTE' and 'FREEBYTE' options.

7. Allocation stop.
8. Reallocation stop.
9. Free stop. These values are used by the library to halt the program when run inside a debugger whenever a specified allocation index is allocated, reallocated or freed. These can be changed at run-time using the 'ALLOCSTOP', 'REALLOCSTOP' and 'FREESTOP' options.
10. Unfreed abort. This value is used when the program terminates and is used by the library to check if there are more than a given number of unfreed memory allocations. If there are then the library will cause the program to abort with an error. It can be changed at run-time using the 'UNFREEDABORT' option.
11. Small boundary.
12. Medium boundary.
13. Large boundary. These values are used in memory allocation profiling and specify the boundaries in bytes between small, medium, large and extra large allocations. These can be changed at run-time using the 'SMALLBOUND', 'MEDIUMBOUND' and 'LARGEBOUND' options.
14. Lower check range.
15. Upper check range.
16. Check frequency. These values specify the range of allocation indices through which the library will physically check every area of free memory and every overflow buffer for errors, along with the frequency at which to make the checks. A dash specifies that either the lower or upper range is infinite, but if they are both zero then no such checking will ever be performed, thus speeding up execution speed dramatically. The check frequency indicates the number of memory allocation events that must occur in between checking the heap. The library defaults to performing no such checks. This can be changed at run-time using the 'CHECK' option.
17. Failure frequency.
18. Failure seed. These values are used to specify if random memory allocation failures should occur during program execution, for the purposes of stress testing a program. If the failure frequency is zero then no random failures will occur, but if it is greater than zero then the higher the number, the less frequent the failures. The failure seed is used internally by the mpatrol library when generating random numbers. If it is zero then the seed will be set randomly, but if it is greater than zero then it will be used to generate a predictable sequence of random numbers; i.e. two runs of the same program with the same failure frequencies and the same failure seeds will generate exactly the same sequence of failures.
19. Prologue function.
20. Epilogue function.
21. Handler function. These values contain addresses or names of functions that have been installed as callback functions for the library. These functions, if set, will be called from the library at appropriate times during program execution in order to handle specific events. These can be changed at compile-time using the `__mp_prologue()`, `__mp_epilogue()` and `__mp_nomemory()` functions.
22. Log file. Simply contains the name of the file where all mpatrol library diagnostics go to. It can be changed at run-time using the 'LOGFILE' option.
23. Profiling file. Contains the name of the file where all of the mpatrol library memory allocation profiling information goes when the 'PROF' option is used. It can be changed at run-time using the 'PROFFILE' option.
24. Tracing file. Contains the name of the file where all of the mpatrol library memory allocation tracing information goes when the 'TRACE' option is used. It can be changed at run-time using the 'TRACEFILE' option.

25. Program filename. Contains the full pathname to the program's executable file. This is used by the mpatrol library to read the symbol table in order to provide symbolic information in function call stacks. It can be changed at run-time using the '`PROGFILE`' option.
26. Symbols read. This value contains the total number of symbols read from a program's executable file and/or the dynamic linker, if applicable.
27. Autosave count. This value contains the frequency at which the mpatrol library should periodically write the profiling data to the profiling output file. When the total number of profiled memory allocations and deallocations is a multiple of this number then the current profiling information will be written to the profiling output file. It can be changed at run-time using the '`AUTOSAVE`' option.
28. Freed queue size. This value contains the maximum number of freed memory allocations that will be stored in the freed queue if the '`NOFREE`' option is used. Once the freed queue becomes full then the oldest freed allocation in the queue will be returned to the free memory pool for reuse every time an existing memory allocation is freed. If this value is zero then the freed queue will never contain any freed allocations. It can be changed at run-time using the '`NOFREE`' option.
29. Allocation count. This value contains the total number of memory allocations that were created by the mpatrol library. This value may be more than expected if the mpatrol library makes any memory allocations during initialisation.
30. Allocation peak. This value contains the peak memory usage set by the program when running; the peak number of memory allocations, and also the peak number of bytes allocated in parentheses (the two numbers may peak at different times throughout the lifetime of the program). This value may be more than expected if the mpatrol library makes any memory allocations during initialisation.
31. Allocation limit. This value is used to limit the amount of memory that can be allocated by a program, which can be useful for stress-testing in simulated low memory conditions. It can be changed at run-time using the '`LIMIT`' option.
32. Allocated blocks.
33. Freed blocks.
34. Free blocks. These values contain the total number of allocated, freed and free blocks at the time the summary was produced. A freed block is an allocated block that has been freed but has not been returned to the free memory list for later allocation. These values may be different from those expected if the mpatrol library makes any memory allocations during initialisation. In this example a large amount of memory is used by the system object file access library which is used for reading the symbols from the program's executable file and any shared libraries that it requires.
35. Internal blocks. This value contains the total number of memory blocks (of varying sizes) that have been allocated from the system for the mpatrol library to use internally. These memory blocks will be write-protected on systems that support memory protection in order to prevent the program from corrupting the library's data structures. This can be overridden at run-time using the '`NOPROTECT`' option in order to speed up program execution slightly.
36. Total heap usage. This value contains the total amount of system heap memory that has been allocated by the mpatrol library.
37. Total compared.
38. Total located.
39. Total copied.
40. Total set. These values contain the total number of bytes that have been tracked by the mpatrol library in byte comparison operations (such as `memcmp()`), byte location operations (such as `memchr()`, byte copy operations (such as `memcpy()`) and byte set operations (such as `memset()`) respectively. They do not take into account any other such operations that occur outwith these functions, such as loading and storing from machine instructions.

41. Total warnings.
42. Total errors. The library keeps a count of the total number of warnings and errors it has displayed so that you can quickly work out this information at program termination.

12.2 Detecting incorrect reuse of freed memory

The next example uses '`tests/fail/test2.c`' to illustrate how the mpatrol library can detect whereabouts on the heap an address belongs.

```
/*
 * Allocates a block of 16 bytes and then immediately frees it.  An
 * attempt is then made to double the size of the original block.
 */


#include "mpatrol.h"


int main(void)
{
    char *p;

    if (p = (char *) malloc(16))
    {
        free(p);
        p = (char *) realloc(p, 32);
    }
    return EXIT_SUCCESS;
}
```

The relevant excerpts from '`mpatrol.log`' appear below. The format of the log messages should be familiar to you now.

```
ALLOC: malloc (52, 16 bytes, 4 bytes) [main|test2.c|36]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

returns 0x080620E8

FREE: free (0x080620E8) [main|test2.c|38]
        0x08049456 main+70
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

    0x080620E8 (16 bytes) {malloc:52:0} [main|test2.c|36]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

REALLOC: realloc (0x080620E8, 32 bytes, 4 bytes) [main|test2.c|39]
        0x08049476 main+102
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33
```

```
ERROR: [NOTALL]: realloc: 0x080620E8 has not been allocated

returns 0x00000000
```

The mpatrol library stores all of its information about allocated and free memory in tree structures so that it can quickly determine if an address belongs to allocated or free memory, or if it even exists in the heap that is managed by mpatrol. The above example should illustrate this since after the allocation had been freed, the library recognised this and reported an error. It was possible for the program to continue execution even after that error since mpatrol could recover from it and return 'NULL'.

It is possible for mpatrol to give even more useful diagnostics in the above situation by using the 'NOFREE' option. This prevents the library from returning any freed allocations to the free memory pool, by preserving any information about them and marking them as freed. If you add the 'NOFREE=1' option to the MPATROL_OPTIONS environment variable you should see the following entries in 'mpatrol.log' instead.

```
ALLOC: malloc (52, 16 bytes, 4 bytes) [main|test2.c|36]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

returns 0x08062F54

FREE: free (0x08062F54) [main|test2.c|38]
        0x08049456 main+70
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

    0x08062F54 (16 bytes) {malloc:52:0} [main|test2.c|36]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

REALLOC: realloc (0x08062F54, 32 bytes, 4 bytes) [main|test2.c|39]
        0x08049476 main+102
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

ERROR: [PRVFRD]: realloc: 0x08062F54 was freed with free
    0x08062F54 (16 bytes) {free:52:0} [main|test2.c|38]
        0x08049456 main+70
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

returns 0x00000000
```

Note the extra information reported by realloc() since the library knows all of the details about the freed memory allocation and when it was freed.

The 'NOFREE' option can potentially use up much more system memory than normal if it is given a large numerical argument since it effectively instructs the mpatrol library to allocate new memory for every single memory allocation or reallocation. It can also slow down program execution when overflow buffers are used, since with each new memory allocation the library needs to check more and more overflow buffers every time it is called. However, with a low numerical argument it can be quite useful for problems such as this one. The test in '`tests/fail/test3.c`' has a similar situation.

The numerical argument specified with the '`NOFREE`' option indicates the number of recently-freed memory allocations that are to be delayed from being returned to the free memory pool, with a value of zero meaning that all freed memory allocations will immediately be reused. Obviously, in an ideal world it would be nice to be able to specify '`NOFREE=`'*huge-number* all the time, but this will gradually use up more and more memory since no system heap memory will ever be reused. Supplying a smaller number to the '`NOFREE`' option allows you to make a compromise by storing the details of only the most recently-freed memory allocations. How many details you wish to store is up to you.

Normally, the '`NOFREE`' option will cause the library to fill all freed memory allocations with the free byte. However, the original contents of such allocations can be preserved with the '`PRESERVE`' option. This could help in situations when you need to determine exactly if a program is relying on the contents of freed memory.

12.3 Detecting use of free memory

This next example illustrates how the mpatrol library is able to check to see if anything has been written into free memory. The test is located in '`tests/fail/test4.c`' and simply writes a single byte into free memory.

```
/*
 * Allocates a block of 16 bytes and then immediately frees it.  A
 * NULL character is written into the middle of the freed memory.
 */


#include "mpatrol.h"


int main(void)
{
    char *p;

    if (p = (char *) malloc(16))
    {
        free(p);
        p[8] = '\0';
    }
    return EXIT_SUCCESS;
}
```

The following output was produced as part of '`mpatrol.log`'. Note that this test was run using the same `MPATROL_OPTIONS` settings as the last example, but make sure that '`PRESERVE`' is not set.

```
ERROR: [FRDCOR]: freed allocation 0x08062F54 has memory corruption at 0x08062F5C
        0x08062F5C  00555555 55555555                    .UUUUUUU

    0x08062F54 (16 bytes) {free:52:0} [main|test4.c|38]
        0x08049456 main+70
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33
```

The library was able to detect that something had been written into free memory and could report on the memory allocation that was overwritten. However, these checks are only performed whenever a function in the mpatrol library is called if the 'CHECK' option is used, or at the end of program execution. In the example above, the code which wrote into free memory could have been miles away from where the library detected the error since we were not using the 'CHECK' option. However, adding 'CHECK=-' to the MPATROL_OPTIONS environment variable doesn't really help much since the next mpatrol function that is called is the one to terminate the library anyway.

On platforms that support memory protection, the library also supports the 'PAGEALLOC' option. This option instructs the library to force every single memory allocation to have a size which is a multiple of the system page size. Although the library still stores the original requested size, it effectively means that no two memory allocations occupy the same page of memory. It can then use page protection (which only operates on pages of memory) to protect all free memory from being read from or written to, and uses similar features to install a page of overflow buffer on either side of the allocation.

However, if the requested size for the memory allocation was not a multiple of the page size this means that there will still be unused space left over in the allocated pages. This problem is solved by turning the unused space into overflow buffers that will be checked in the normal way. The positioning of the allocation within its pages is also important. If you want to check for illegal reads from the borders of the memory allocation, unless it fits exactly into its pages then there is a chance that a program could illegally read the right-most overflow buffer if the allocation was left-aligned, or vice-versa. Two settings therefore exist for the 'PAGEALLOC' option: 'LOWER' and 'UPPER'. They refer to the placement of every memory allocation within its constituent pages.

The following diagram illustrates the 'PAGEALLOC' option. In the diagram, the system page size is assumed to be 16 bytes (very unlikely, but will serve for this example) and each character represents 1 byte.

```
x = allocated memory
o = overflow buffer (filled with the overflow byte)
. = overflow buffer page (read and write protected)

PAGEALLOC=LOWER, allocation size is 16 bytes or
PAGEALLOC=UPPER, allocation size is 16 bytes:
    ................xxxxxxxxxxxxxxxx................

PAGEALLOC=LOWER, allocation size is 8 bytes:
    ................xxxxxxxxoooooooo................

PAGEALLOC=UPPER, allocation size is 8 bytes:
    ................ooooooooxxxxxxxx................
```

In our original example, if the 'PAGEALLOC=LOWER' option is added to the MPATROL_OPTIONS environment variable then the following error will be produced instead of the original error.

```
ERROR: [ILLMEM]: illegal memory access at address 0x081C6008
    0x081C6000 (16 bytes) {free:52:0} [main|test4.c|38]
        0x08049456 main+70
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33

    call stack
        0x0804945F main+79
        0x4007C9CB __libc_start_main+255
```

```
             0x08049381 _start+33
```

On systems that support memory protection, the mpatrol library has a built-in signal handler which catches illegal memory accesses and terminates the program. In the above case, the freed memory was made write-protected and so could not be written to. The underlying virtual memory system in the operating system noticed this and signaled this to the library immediately after it happened.

Along with the details of the freed memory allocation that was being written to, the library also attempts to display the function call stack for the location in the program that caused the illegal memory access, although this can be quite unreliable. A better solution would be to run the program in a debugger to catch the illegal memory access.

Note that the '`PAGEALLOC`' option also modifies the behaviour of the '`NOFREE`' and '`PRESERVE`' options when used together. The memory allocation being freed will always be made write-protected when the '`PRESERVE`' option is used, otherwise it will also be made read-protected to prevent further accesses.

Note also that the '`PAGEALLOC=UPPER`' option is potentially much less efficient at catching illegal memory accesses than the '`PAGEALLOC=LOWER`' option. This is due to alignment requirements, since an allocation of 1 byte requiring an alignment of 16 bytes cannot be placed at the very end of a page of size 4096 bytes. The following diagram illustrates this, using the same page size as the last diagram.

```
x = allocated memory
o = overflow buffer (filled with the overflow byte)
. = overflow buffer page (read and write protected)

PAGEALLOC=UPPER, allocation size is 16 bytes, alignment is 8 bytes:
    ................xxxxxxxxxxxxxxxx................

PAGEALLOC=UPPER, allocation size is 3 bytes, alignment is 1 byte:
    ................oooooooooooooxxx................

PAGEALLOC=UPPER, allocation size is 3 bytes, alignment is 8 bytes:
    ................ooooooooxxxooooo................
```

Everything is OK until the last allocation, where the alignment requirement means that there must be two overflow buffers. This slows down program execution since the library must check an additional overflow buffer, and also means that the program would have to read six bytes beyond the end of the allocation before the illegal memory access would be detected.

12.4 Using overflow buffers

This example illustrates the use of overflow buffers and so the `MPATROL_OPTIONS` environment variable should have '`OFLOWSIZE=2`' and '`CHECK=-`' added to it. However, turn off any '`PAGEALLOC`' options for the purposes of this example. The test is located in '`tests/fail/test5.c`', and '`tests/fail/test6.c`' is very similar.

```
/*
 * Allocates a block of 16 bytes and then copies a string of 16
 * bytes into the block.  However, the string is copied to 1 byte
 * before the allocated block which writes before the start of the
 * block.  This test must be run with an OFLOWSIZE greater than 0.
 */


#include "mpatrol.h"
```

```
int main(void)
{
    char *p;

    if (p = (char *) malloc(16))
    {
        strcpy(p - 1, "this test fails!");
        free(p);
    }
    return EXIT_SUCCESS;
}
```

The following error should be produced in '`mpatrol.log`'.

```
ERROR: [ALLOVF]: allocation 0x08062FB8 has a corrupted overflow buffer at
                 0x08062FB7
        0x08062FB6  AA74                                .t

    0x08062FB8 (16 bytes) {malloc:52:0} [main|test5.c|38]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33
```

Once again, the library attempts to show you as much detail as possible about where the corruption occurred. Along with showing you a memory dump of the overflow buffer that was corrupted, it also shows you the allocation to which the overflow buffer belongs.

Using overflow buffers and the '`CHECK=-`' option can reduce the speed of program execution since the library has to check every buffer whenever it is called, and if the buffers are larger then they'll take longer to check and will use up more memory. However, larger buffers mean that there is less chance of the program writing past one memory allocation into another.

Alternatively, the '`CHECK`' option can be used to limit the number of checks that the library has to perform, thus speeding up program execution. This option specifies a range of allocation indices through which the library will check overflow buffers and free memory for corruption. Such checks occur when they normally would, but only if the current allocation index falls within the specified range. This feature can be used when there is a suspicion that free memory corruption or overflow buffer corruption occurs at a certain point during program execution, but checking them at every library call would take too long. You can also specify a frequency at which to check the heap using the '`CHECK`' option. This can be used when attempting to narrow down the search for where heap corruption occurs.

On systems which support software watch points, there is an extra option called '`OFLOWWATCH`' which allows additional memory protection. Watch points allow individual bytes to be read and/or write protected as opposed to just pages. The '`OFLOWWATCH`' option installs software watch points at every overflow buffer instead of requiring the library to check the integrity of the overflow buffers, and can be used in combination with '`PAGEALLOC`'. However, software watch points slow down program execution to a crawl since every machine instruction must be checked individually by the system to see if it accesses a watch point area. Slowing the program down by a factor of 10,000 is not uncommon on some systems when the '`OFLOWWATCH`' option is used.

12.5 Checking memory accesses

For the ultimate in heap checking, if you are using the GNU compiler you can use the '`-fcheck-memory-usage`' option. This instructs the compiler to place error-checking calls before each read or write to memory. The functions that are called then check to ensure that the memory access does not overflow a heap memory allocation or access free memory.

The following test (which can be found in '`tests/fail/test17.c`') has an example of a read from memory which overflows a memory allocation's boundaries.

```
/*
 * Allocates a single byte of memory and then attempts to read the
 * byte as a word, resulting in some uninitialised bytes being read.
 * This can sometimes be detected with PAGEALLOC=UPPER but can always
 * be detected with OFLOWWATCH or by using the -fcheck-memory-usage
 * option of gcc.
 */


#include "mpatrol.h"


int main(void)
{
    int *p;
    int r;

    if (p = (int *) calloc(1, 1))
    {
        r = p[0];
        free(p);
    }
    return EXIT_SUCCESS;
}
```

For this example, the above test must be compiled with `gcc` with the '`-fcheck-memory-usage`' option on the compiler command line and linked with the mpatrol library. Normally, the test will pass and not cause any problems, since most malloc libraries will allocate at least one word anyway. However, there are some instances where that will not be the case, especially on systems where misaligned memory accesses are legal. Also, if the implementation of `calloc()` only initialised the number of bytes requested then the number read back might not be zero.

If you now run the program it should abort and produce something similar to the following in the resulting '`mpatrol.log`'.

```
ERROR: [RNGOVF]: range [0x00022568,0x0002256B] overflows
                 [0x00022568,0x00022568]
    0x00022568 (1 byte) {calloc:19:0} [main|test17.c|40]
        0x00010A0C main+96
        0x0001087C _start+100
```

As you can see, the mpatrol library detected a read beyond the boundaries of the one byte memory allocation starting at '`0x00022568`'.

12.6 Bad memory operations

In C there are several basic memory operation functions that are often called to perform tasks such as clearing memory, copying memory, etc. The mpatrol library contains replacements for these which allow for better checking of their arguments to prevent reading and writing past the boundaries of existing memory allocations. The following source can be found in 'tests/fail/test9.c'.

```
/*
 * Allocates a block of 16 bytes and then attempts to zero the contents of
 * the block.  However, a zero byte is also written 1 byte before and 1
 * byte after the allocated block, resulting in an error in the log file.
 */


#include "mpatrol.h"


int main(void)
{
    char *p;

    if (p = (char *) malloc(16))
    {
        memset(p - 1, 0, 18);
        free(p);
    }
    return EXIT_SUCCESS;
}
```

When this is compiled and run, the following should appear in the log file.

```
ERROR: [RNGOVF]: memset: range [0x08062FB7,0x08062FC8] overflows
                 [0x08062FB8,0x08062FC7]
    0x08062FB8 (16 bytes) {malloc:52:0} [main|test9.c|37]
        0x0804942F main+31
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33
```

As you can see, the library detected that the `memset()` function would have written past the boundaries of the memory allocation and reported this to you. It then proceeded to ignore the request to copy the memory and continued with the execution of the program[2]. Note that this will only be done for known memory allocations. Reading and writing past the boundaries of static and stack memory allocations cannot be detected in this way.

If the 'LOGMEMORY' option is added to the `MPATROL_OPTIONS` environment variable then it is possible to see a log of all the mpatrol library memory operation functions that were called during program execution. For example, adding this option and running the above program again will produce something similar to the following.

```
MEMSET: memset (0x08062FB7, 18 bytes, 0x00) [main|test9.c|39]
        0x0804945B main+75
        0x4007C9CB __libc_start_main+255
        0x08049381 _start+33
```

This is similar to the tracing produced for memory allocation functions, except that the arguments in parentheses mean different things. For 'MEMSET', the first argument represents the start of the memory block to set, the second argument represents the number of bytes to set and the third argument represents the actual byte to set.

[2] The error can be turned into a warning with the 'ALLOWOFLOW' option which will also force the operation to be performed.

For 'MEMCOPY', the first argument represents the source memory block, the second argument represents the destination memory block, the third argument represents the number of bytes to copy and the fourth argument represents a byte to copy up to if `memccpy()` is being called. This is similar for 'MEMCMP'.

For 'MEMFIND', the first and second arguments represent the source memory block and its length, while the third and fourth arguments represent the memory block to search for and its length. In the implementation for `memchr()`, the byte to search for is copied to a one byte buffer and the address of that buffer is used as the memory block to search for.

Note that as with the memory allocation functions, 'MEMCMP', 'MEMFIND', 'MEMCOPY' and 'MEMSET' are used to generalise the types of operations being performed and are followed by the names of the actual functions being used. In some cases the functions may use a different ordering of parameters than that shown.

12.7 Incompatible function calls

This example illustrates how the mpatrol library checks for calls to incompatible pairs of memory allocation functions. It requires the use of C++, although does not use any C++ features except for overloaded operators. The source is in '`tests/fail/test7.c`', and '`tests/fail/test8.c`' is similar.

```
23  /*
24   * Allocates a block of 16 bytes using C++ operator new[] and then
25   * attempts to free it using C++ operator delete.
26   */


29  #include "mpatrol.h"


32  int main(void)
33  {
34      char *p;

36      p = new char[16];
37      delete p;
38      return EXIT_SUCCESS;
39  }
```

The relevant parts of '`mpatrol.log`' are shown below.

```
ALLOC: operator new[] (74, 16 bytes, 4 bytes) [int main()|test7.c|36]
        0x0804955D main+13
        0x400DB9CB __libc_start_main+255
        0x080494C1 _start+33

returns 0x08062FC0

FREE: operator delete (0x08062FC0) [int main()|test7.c|37]
        0x0804956E main+30
        0x400DB9CB __libc_start_main+255
        0x080494C1 _start+33

ERROR: [INCOMP]: operator delete: 0x08062FC0 was allocated with operator new[]
    0x08062FC0 (16 bytes) {operator new[]:74:0} [int main()|test7.c|36]
```

```
               0x0804955D main+13
               0x400DB9CB __libc_start_main+255
               0x080494C1 _start+33
```

This shows a call to `operator new[]`, closely followed by a call to `operator delete`. However, in C++ calls to `operator new[]` must be matched by calls to `operator delete[]` and not `operator delete`. Hence, the library reports this as an error and does not free the memory allocation.

12.8 The `alloca()` functions

There are two examples of using `alloca()` and its related functions in '`tests/pass/test8.c`' and '`tests/fail/test16.c`'. Both rely on mpatrol having full call stack traceback support, although they will work (albeit with slightly different results) on systems that do not.

The first test simply illustrates the use of `alloca()` and how its memory allocations are freed when they are no longer in use.

```
/*
 * Tests alloca() and related functions via nested function calls.
 * The final output should be a horizontal pyramid of plus signs
 * followed by a horizontal pyramid of minus signs.
 */


#include "mpatrol.h"
#include <stdio.h>


char *f1(char *s)
{
    char *t;
    size_t l;

    l = strlen(s) + 1;
    if ((t = (char *) alloca(l + 1)) == NULL)
        return NULL;
    memcpy(t, s, l);
    t[l - 1] = t[l - 2];
    t[l] = '\0';
    return strdup(t);
}


char *f2(char *s)
{
    char *t;
    size_t l;

    l = strlen(s) - 1;
    if ((t = (char *) alloca(l + 1)) == NULL)
        return NULL;
    memcpy(t, s, l + 1);
    t[l] = '\0';
```

```
    return strdup(t);
}


int f(char *s, size_t l)
{
    char *t;
    size_t i;

    puts(s);
    for (i = 0; i < l; i++)
    {
        if (((t = f1(s)) == NULL) ||
            ((s = (char *) alloca(strlen(t) + 1)) == NULL))
            return 0;
        strcpy(s, t);
        free(t);
        puts(s);
    }
    for (i = 0; i < l; i++)
    {
        if (((t = f2(s)) == NULL) ||
            ((s = (char *) alloca(strlen(t) + 1)) == NULL))
            return 0;
        strcpy(s, t);
        free(t);
        puts(s);
    }
    return 1;
}


int main(void)
{
    char *s;

    s = strdupa("+");
    if (!f(s, 4))
        exit(EXIT_FAILURE);
    dealloca(s);
    s = strdupa("-");
    if (!f(s, 4))
        exit(EXIT_FAILURE);
    dealloca(s);
    return EXIT_SUCCESS;
}
```

When compiled and run, you should get the following output.

```
+
++
+++
++++
```

```
+++++
++++
+++
++
+
-
--
---
----
-----
----
---
--
-
```

If you run it again, this time with the `MPATROL_OPTIONS` environment variable set to ‘`LOGALLOCS`’ and ‘`LOGFREES`’, you should see the following in the newly-generated ‘`mpatrol.log`’ file. Note that the ‘`...`’ marks text that has been removed.

```
ALLOC: strdupa (1, 2 bytes, 1 byte) [main|test8.c|95] (char x 2)
        0x000138F0 main+52
        0x00013350 _start+100

returns 0x0008C000

ALLOC: alloca (2, 3 bytes, 8 bytes) [f1|test8.c|40]
        0x000134CC f1+76
        0x000136D8 f+68
        0x00013904 main+72
        0x00013350 _start+100

returns 0x0008C008

ALLOC: strdup (3, 3 bytes, 1 byte) [f1|test8.c|45] (char x 3)
        0x00013584 f1+260
        0x000136D8 f+68
        0x00013904 main+72
        0x00013350 _start+100

returns 0x0008C002

FREE: alloca (0x0008C008) [f|test8.c|72]
        0x00013728 f+148
        0x00013904 main+72
        0x00013350 _start+100

    0x0008C008 (3 bytes) {alloca:2:0} [f1|test8.c|40]
        0x000134CC f1+76
        0x000136D8 f+68
        0x00013904 main+72
        0x00013350 _start+100

ALLOC: alloca (4, 3 bytes, 8 bytes) [f|test8.c|72]
```

```
        0x00013728 f+148
        0x00013904 main+72
        0x00013350 _start+100

returns 0x0008C008

...

FREE: alloca (0x0008C040) [main|test8.c|102]
        0x000139C8 main+268
        0x00013350 _start+100

    0x0008C040 (2 bytes) {alloca:50:0} [f|test8.c|81]
        0x00013828 f+404
        0x00013988 main+204
        0x00013350 _start+100

FREE: alloca (0x0008C038) [main|test8.c|102]
        0x000139C8 main+268
        0x00013350 _start+100

    0x0008C038 (3 bytes) {alloca:47:0} [f|test8.c|81]
        0x00013828 f+404
        0x00013988 main+204
        0x00013350 _start+100

...

FREE: alloca (0x0008C010) [main|test8.c|102]
        0x000139C8 main+268
        0x00013350 _start+100

    0x0008C010 (4 bytes) {alloca:32:0} [f|test8.c|72]
        0x00013728 f+148
        0x00013988 main+204
        0x00013350 _start+100

FREE: alloca (0x0008C008) [main|test8.c|102]
        0x000139C8 main+268
        0x00013350 _start+100

    0x0008C008 (3 bytes) {alloca:29:0} [f|test8.c|72]
        0x00013728 f+148
        0x00013988 main+204
        0x00013350 _start+100

FREE: dealloca (0x0008C000) [main|test8.c|102]
        0x000139C8 main+268
        0x00013350 _start+100

    0x0008C000 (2 bytes) {strdupa:26:0} [main|test8.c|99] (char x 2)
```

```
        0x00013974 main+184
        0x00013350 _start+100
```

After the first call to `strdupa()`, there is a call to `alloca()` followed by a call to `strdup()`. Because the memory allocation made by `strdupa()` is at the top level of the program it cannot automatically be freed until `main()` returns. However, at the next call to `alloca()` in `f()`, the mpatrol library notices that the memory allocation that was made by `alloca()` in `f1()` can be freed since `f1()` has returned. The relevant allocation is then freed before making the next memory allocation. You can see how it makes its decision by examining the call stack at the point of deallocation.

However, all of the memory allocations made by `alloca()` in `f()` cannot be freed until `f()` returns. This can be seen in the two sets of eight consecutive deallocations in the log file, each set followed by a call to `dealloca()`. The `dealloca()` function explicitly frees a memory allocation that was made by the `alloca()` family of functions, but these calls are not really necessary as all of these memory allocations would be freed anyway when `main()` returns. The call to `dealloca()` is really only necessary to force a deallocation for a specific purpose at a certain point in the program. Note that implicit deallocations are marked as being done by `alloca()` while explicit deallocations are marked as being done by `dealloca()`.

The second test illustrates how the mpatrol library can help debug `alloca()`-related problems by treating such memory allocations as normal heap allocations.

```
/*
 * Duplicates a string using alloca() and then returns the address
 * of the allocation.  This is illegal since the memory allocated
 * by alloca() will be freed when the function returns.  The call
 * to memcpy() will then corrupt free memory and the call to free()
 * will attempt to free an invalid pointer.
 */


#include "mpatrol.h"
#include <stdio.h>


char *f(size_t l)
{
    return (char *) alloca(l);
}


char *g(char *s)
{
    char *t;
    size_t l;

    l = strlen(s) + 1;
    if (t = f(l))
        memcpy(t, s, l);
    return t;
}


int main(void)
```

```
{
    char *s;

    s = g("test");
    free(s);
    return EXIT_SUCCESS;
}
```

If you compile and run this example with the `MPATROL_OPTIONS` environment variable containing the options ‘`LOGALL`’ and ‘`NOFREE=1`’ you should see the following in `mpatrol.log`.

```
ALLOC: alloca (1, 5 bytes, 8 bytes) [f|test16.c|38]
        0x0001346C f+52
        0x000134A8 g+40
        0x00013524 main+20
        0x00013308 _start+100

returns 0x0008C000

FREE: alloca (0x0008C000) [g|test16.c|49]
        0x000134F8 g+120
        0x00013524 main+20
        0x00013308 _start+100

    0x0008C000 (5 bytes) {alloca:1:0} [f|test16.c|38]
        0x0001346C f+52
        0x000134A8 g+40
        0x00013524 main+20
        0x00013308 _start+100

MEMCOPY: memcpy (0x0001F760, 0x0008C000, 5 bytes, 0x00) [g|test16.c|49]
        0x000134F8 g+120
        0x00013524 main+20
        0x00013308 _start+100

ERROR: [FRDOPN]: memcpy: attempt to perform operation on freed memory
    0x0008C000 (5 bytes) {alloca:1:0} [g|test16.c|49]
        0x000134F8 g+120
        0x00013524 main+20
        0x00013308 _start+100

returns 0x0008C000

FREE: free (0x0008C000) [main|test16.c|59]
        0x00013550 main+64
        0x00013308 _start+100

ERROR: [PRVFRD]: free: 0x0008C000 was freed with alloca
    0x0008C000 (5 bytes) {alloca:1:0} [g|test16.c|49]
        0x000134F8 g+120
        0x00013524 main+20
        0x00013308 _start+100
```

As you can see, memory allocations made by `alloca()` are treated in almost exactly the same way as normal memory allocations, with the result that errors similar to those above can be detected by the mpatrol library. The only real difference between the two types of memory allocations is that allocations made by the `alloca()` family of functions will never show up in the list of unfreed memory allocations.

12.9 The `MP_MALLOC()` functions

The mpatrol library comes with a set of alternative dynamic memory allocation functions for C. These allow it to record the type and type size of every memory allocation made through these functions, which can be very useful for debugging purposes. It also means that the alignment for each memory allocation can be determined according to its type. The following test can be found in '`tests/pass/test9.c`'.

```
/*
 * Allocates 16 floats and then resizes the allocation to 8 floats and
 * frees them.  Then allocates 16 integers and resizes the allocation
 * to 32 integers before freeing them.  Finally, duplicates a string
 * and then frees it.
 */


#include "mpatrol.h"


int main(void)
{
    float *f;
    int *i;
    char *s;

    MP_MALLOC(f, 16, float);
    MP_REALLOC(f, 8, float);
    MP_FREE(f);
    MP_CALLOC(i, 16, int);
    MP_REALLOC(i, 32, int);
    MP_FREE(i);
    MP_STRDUP(s, "test");
    MP_FREE(s);
    return EXIT_SUCCESS;
}
```

If this test is compiled and linked with the mpatrol library and then run with the '`LOGALL`' option, the following output will be seen in the mpatrol log file.

```
ALLOC: xmalloc (84, 64 bytes, 4 bytes) [main|test9.c|40] (float x 16)
        0x0804AC36 main+38
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

returns 0x080510E8

REALLOC: xrealloc (0x080510E8, 32 bytes, 4 bytes) [main|test9.c|41] (float x 8)
        0x0804AC60 main+80
```

```
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

    0x080510E8 (64 bytes) {xmalloc:84:0} [main|test9.c|40] (float x 16)
        0x0804AC36 main+38
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

returns 0x080510E8

FREE: xfree (0x080510E8) [main|test9.c|42]
        0x0804AC7F main+111
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

    0x080510E8 (32 bytes) {xrealloc:84:1} [main|test9.c|41] (float x 8)
        0x0804AC60 main+80
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

ALLOC: xcalloc (85, 64 bytes, 4 bytes) [main|test9.c|43] (int x 16)
        0x0804ACB2 main+162
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

returns 0x080510E8

REALLOC: xrealloc (0x080510E8, 128 bytes, 4 bytes) [main|test9.c|44] (int x 32)
        0x0804ACDF main+207
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

    0x080510E8 (64 bytes) {xcalloc:85:0} [main|test9.c|43] (int x 16)
        0x0804ACB2 main+162
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

returns 0x080510E8

FREE: xfree (0x080510E8) [main|test9.c|45]
        0x0804ACFE main+238
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

    0x080510E8 (128 bytes) {xrealloc:85:1} [main|test9.c|44] (int x 32)
        0x0804ACDF main+207
        0x400A09CB __libc_start_main+255
        0x0804AB81 _start+33

ALLOC: xstrdup (86, 5 bytes, 1 byte) [main|test9.c|46] (char x 5)
        0x0804AD2E main+286
```

```
            0x400A09CB __libc_start_main+255
            0x0804AB81 _start+33

    returns 0x080510E5

    FREE: xfree (0x080510E5) [main|test9.c|47]
            0x0804AD4F main+319
            0x400A09CB __libc_start_main+255
            0x0804AB81 _start+33

        0x080510E5 (5 bytes) {xstrdup:86:0} [main|test9.c|46] (char x 5)
            0x0804AD2E main+286
            0x400A09CB __libc_start_main+255
            0x0804AB81 _start+33
```

As you can see, the type and number of items allocated of that type are associated with each memory allocation. The function names that are logged as having made the memory allocations are from the `xmalloc()` family of functions since that is how the `MP_MALLOC()` family of functions are implemented.

12.10 Additional useful information

This last example illustrates the various '`SHOW`' options that are available for displaying additional information from the mpatrol library at program termination. It also shows how to easily detect memory leaks. Use the '`OFLOWSIZE=16`', '`NOFREE=16`' and '`SHOWALL`' options in `MPATROL_OPTIONS` before running.

```
/*
 * Introduces a memory leak by clobbering a pointer with a new
 * memory allocation.  Use with SHOWUNFREED to display it.
 */


#include "mpatrol.h"


int main(void)
{
    void *p;

    p = malloc(4);
    p = malloc(4);
    if (p != NULL)
        free(p);
    return EXIT_SUCCESS;
}
```

The information that we are interested in comes after the summary of library statistics generated in the log file. The first block of data shows a memory map of the heap that is being handled by mpatrol. This can be used to see graphically where a particular allocation is located, or to look for memory fragmentation. The '`SHOWMAP`' option also displays this information.

Note that gaps in the memory map can either be due to space used by internal memory blocks or to some other memory allocation library using up space. On some systems that don't have virtual memory, gaps are likely to be owned by other processes or belong to the system free memory list. The '...' marks text that has been removed.

```
memory map:
    ...
  / 0x0002FDD0-0x0002FDDF overflow (16 bytes)
 |+ 0x0002FDE0-0x0002FE03 allocated (36 bytes) {calloc:13:0} [-|-|-]
  \ 0x0002FE04-0x0002FE13 overflow (16 bytes)
--- 0x0002FE14-0x0002FE17 free (4 bytes)
  / 0x0002FE18-0x0002FE27 overflow (16 bytes)
 |+ 0x0002FE28-0x0002FF18 allocated (241 bytes) {calloc:15:0} [-|-|-]
  \ 0x0002FF19-0x0002FF28 overflow (16 bytes)
--- 0x0002FF29-0x0002FF2F free (7 bytes)
  / 0x0002FF30-0x0002FF3F overflow (16 bytes)
 |+ 0x0002FF40-0x0002FF93 allocated (84 bytes) {calloc:16:0} [-|-|-]
  \ 0x0002FF94-0x0002FFA3 overflow (16 bytes)
--- 0x0002FFA4-0x0002FFA7 free (4 bytes)
  / 0x0002FFA8-0x0002FFB7 overflow (16 bytes)
 |+ 0x0002FFB8-0x0002FFC4 allocated (13 bytes) {calloc:17:0} [-|-|-]
  \ 0x0002FFC5-0x0002FFD4 overflow (16 bytes)
--- 0x0002FFD5-0x0002FFD7 free (3 bytes)
  / 0x0002FFD8-0x0002FFE7 overflow (16 bytes)
 |+ 0x0002FFE8-0x0002FFEB allocated (4 bytes) {malloc:19:0} [main|test.c|14]
  \ 0x0002FFEC-0x0002FFFB overflow (16 bytes)
--- 0x0002FFFC-0x0002FFFF free (4 bytes)
    --------------------- gap (57344 bytes)
  / 0x0003E000-0x0003E00F overflow (16 bytes)
 |+ 0x0003E010-0x0003EFFF freed (4080 bytes) {free:6:0} [-|-|-]
  \ 0x0003F000-0x0003F00F overflow (16 bytes)
  / 0x0003F010-0x0003F01F overflow (16 bytes)
 |+ 0x0003F020-0x0003F707 freed (1768 bytes) {free:12:0} [-|-|-]
  \ 0x0003F708-0x0003F717 overflow (16 bytes)
--- 0x0003F718-0x0003FFFF free (2280 bytes)
    --------------------- gap (16384 bytes)
  / 0x00044000-0x0004400F overflow (16 bytes)
 |+ 0x00044010-0x00045197 freed (4488 bytes) {free:8:0} [-|-|-]
  \ 0x00045198-0x000451A7 overflow (16 bytes)
  / 0x000451A8-0x000451B7 overflow (16 bytes)
 |+ 0x000451B8-0x000459AF freed (2040 bytes) {free:10:0} [-|-|-]
  \ 0x000459B0-0x000459BF overflow (16 bytes)
  / 0x000459C0-0x000459CF overflow (16 bytes)
 |+ 0x000459D0-0x00045D93 allocated (964 bytes) {calloc:14:0} [-|-|-]
  \ 0x00045D94-0x00045DA3 overflow (16 bytes)
  / 0x00045DA4-0x00045DB3 overflow (16 bytes)
 |+ 0x00045DB4-0x00045DCE allocated (27 bytes) {strdup:18:0} [-|-|-]
  \ 0x00045DCF-0x00045DDE overflow (16 bytes)
--- 0x00045DDF-0x00045DDF free (1 byte)
  / 0x00045DE0-0x00045DEF overflow (16 bytes)
 |+ 0x00045DF0-0x00045DF3 freed (4 bytes) {free:20:0} [main|test.c|17]
  \ 0x00045DF4-0x00045E03 overflow (16 bytes)
--- 0x00045E04-0x00045FFF free (508 bytes)
```

The next block of data shows a summary of all the symbols that could be read from the program's executable file and/or any shared libraries that the program requires. This can be useful to see which symbols have actually been read by the mpatrol library. The 'SHOWSYMBOLS' option also displays this information.

Note that the following data has been dramatically cut down in size for the purposes of this example. The '...' marks text that has been removed.

```
symbols read: 3300
                 0x000108B0 _ex_text0 [a.out] (0 bytes)
    0x000108B0-0x0001097F _start [a.out] (208 bytes)
    0x00010990-0x00010A27 main [a.out] (152 bytes)
                 0x00010A28 _ex_text1 [a.out] (0 bytes)
    0x00010A28-0x00010A77 _init [a.out] (80 bytes)
    0x00010A78-0x00010AC7 _fini [a.out] (80 bytes)
                 0x7FA1FFF8 _ex_text0 [/usr/lib/libc.so.1] (0 bytes)
    0x7FA1FFF8-0x7FA2005F atexit [/usr/lib/libc.so.1] (104 bytes)
    0x7FA20060-0x7FA200EF _exithandle [/usr/lib/libc.so.1] (144 bytes)
    0x7FA20470-0x7FA204EB __dtou [/usr/lib/libc.so.1] (124 bytes)
    0x7FA20500-0x7FA20577 __ftou [/usr/lib/libc.so.1] (120 bytes)
    0x7FA2083C-0x7FA20B2F __div64 [/usr/lib/libc.so.1] (756 bytes)
    0x7FA20B30-0x7FA20DEB __rem64 [/usr/lib/libc.so.1] (700 bytes)
    ...
    0x7FA96858-0x7FA96867 getpid [/usr/lib/libc.so.1] (16 bytes)
    0x7FA96858-0x7FA96867 _getpid [/usr/lib/libc.so.1] (16 bytes)
    0x7FA96868-0x7FA9689F _kill [/usr/lib/libc.so.1] (56 bytes)
    0x7FA96868-0x7FA9689F _libc_kill [/usr/lib/libc.so.1] (56 bytes)
                 0x7FA968A0 _ex_text1 [/usr/lib/libc.so.1] (0 bytes)
    0x7FA968A0-0x7FA968DF _init [/usr/lib/libc.so.1] (64 bytes)
    0x7FA968E0-0x7FA9691F _fini [/usr/lib/libc.so.1] (64 bytes)
    0x7FB105E4-0x7FB1069F memmove [/usr/lib/libc_psr.so.1] (188 bytes)
    0x7FB105E4-0x7FB1069F _memmove [/usr/lib/libc_psr.so.1] (188 bytes)
                 0x7FB106A0 forcpy [/usr/lib/libc_psr.so.1] (0 bytes)
    0x7FB106A0-0x7FB1190B memcpy [/usr/lib/libc_psr.so.1] (4716 bytes)
    0x7FB106A0-0x7FB1190B _memcpy [/usr/lib/libc_psr.so.1] (4716 bytes)
    0x7FB106A0-0x7FB1190B __align_cpy_1 [/usr/lib/libc_psr.so.1] (4716 bytes)
    ...
    0x7FB135B0-0x7FB135D3 __div64 [/usr/lib/libc_psr.so.1] (36 bytes)
    0x7FB135D4-0x7FB135F7 __udiv64 [/usr/lib/libc_psr.so.1] (36 bytes)
    0x7FB135F8-0x7FB1362B __umul64 [/usr/lib/libc_psr.so.1] (52 bytes)
    0x7FB135F8-0x7FB1362B __mul64 [/usr/lib/libc_psr.so.1] (52 bytes)
    0x7FB1362C-0x7FB13657 __urem64 [/usr/lib/libc_psr.so.1] (44 bytes)
    0x7FB13658-0x7FB13683 __rem64 [/usr/lib/libc_psr.so.1] (44 bytes)
                 0x7FB333F8 _ex_text0 [/usr/lib/libelf.so.1] (0 bytes)
    0x7FB333F8-0x7FB3346F _elf32_entsz [/usr/lib/libelf.so.1] (120 bytes)
    0x7FB33470-0x7FB334EB elf32_fsize [/usr/lib/libelf.so.1] (124 bytes)
    0x7FB33470-0x7FB334EB _elf32_fsize [/usr/lib/libelf.so.1] (124 bytes)
    0x7FB334EC-0x7FB3352F _elf32_msize [/usr/lib/libelf.so.1] (68 bytes)
    0x7FB33530-0x7FB335D3 _elf32_mtype [/usr/lib/libelf.so.1] (164 bytes)
    ...
    0x7FB49054-0x7FB4921F _elf_nlist [/usr/lib/libelf.so.1] (460 bytes)
    0x7FB49220-0x7FB4932F nlist [/usr/lib/libelf.so.1] (272 bytes)
    0x7FB49330-0x7FB493E3 _elf_findop [/usr/lib/libelf.so.1] (180 bytes)
```

```
          0x7FB493E4 _ex_text1 [/usr/lib/libelf.so.1] (0 bytes)
0x7FB493E4-0x7FB4941B _init [/usr/lib/libelf.so.1] (56 bytes)
0x7FB4941C-0x7FB49453 _fini [/usr/lib/libelf.so.1] (56 bytes)
0x7FB65818-0x7FB6582F __mp_newlist [/usr/lib/libmpatrol.so.1.3] (24 bytes)
0x7FB65830-0x7FB65853 __mp_addhead [/usr/lib/libmpatrol.so.1.3] (36 bytes)
0x7FB65854-0x7FB6587B __mp_addtail [/usr/lib/libmpatrol.so.1.3] (40 bytes)
0x7FB6587C-0x7FB6589F __mp_prepend [/usr/lib/libmpatrol.so.1.3] (36 bytes)
0x7FB658A0-0x7FB658C3 __mp_insert [/usr/lib/libmpatrol.so.1.3] (36 bytes)
0x7FB658C4-0x7FB658EB __mp_remove [/usr/lib/libmpatrol.so.1.3] (40 bytes)
...
0x7FB725F4-0x7FB7262B memmem [/usr/lib/libmpatrol.so.1.3] (56 bytes)
0x7FB7262C-0x7FB72663 _memmem [/usr/lib/libmpatrol.so.1.3] (56 bytes)
0x7FB72664-0x7FB72697 memcmp [/usr/lib/libmpatrol.so.1.3] (52 bytes)
0x7FB72698-0x7FB726CB _memcmp [/usr/lib/libmpatrol.so.1.3] (52 bytes)
0x7FB726CC-0x7FB726FF bcmp [/usr/lib/libmpatrol.so.1.3] (52 bytes)
0x7FB72700-0x7FB72733 _bcmp [/usr/lib/libmpatrol.so.1.3] (52 bytes)
0x7FB9085C-0x7FB90863 dlinfo [/usr/lib/libdl.so.1] (8 bytes)
0x7FB9085C-0x7FB90863 _dlinfo [/usr/lib/libdl.so.1] (8 bytes)
0x7FB90864-0x7FB9086B dlmap [/usr/lib/libdl.so.1] (8 bytes)
0x7FB90864-0x7FB9086B _dlmap [/usr/lib/libdl.so.1] (8 bytes)
0x7FB9086C-0x7FB90873 dlmopen [/usr/lib/libdl.so.1] (8 bytes)
0x7FB9086C-0x7FB90873 _dlmopen [/usr/lib/libdl.so.1] (8 bytes)
...
0x7FB90894-0x7FB9089B dladdr [/usr/lib/libdl.so.1] (8 bytes)
0x7FB90894-0x7FB9089B _dladdr [/usr/lib/libdl.so.1] (8 bytes)
0x7FB9089C-0x7FB908A3 dldump [/usr/lib/libdl.so.1] (8 bytes)
0x7FB9089C-0x7FB908A3 _dldump [/usr/lib/libdl.so.1] (8 bytes)
0x7FB908A4-0x7FB908AB _ld_concurrency [/usr/lib/libdl.so.1] (8 bytes)
0x7FB908AC-0x7FB908B3 bind_guard [/usr/lib/libdl.so.1] (8 bytes)
```

The next table is really only useful for seeing how much memory fragmentation has occurred in the memory map. It shows a breakdown of the free memory blocks that have either resulted from the mpatrol library allocating uninitialised memory from the system heap or from freeing existing memory allocations. The column on the left shows the size of the free block in bytes and the column on the right shows the number of blocks of that size that are available. The 'SHOWFREE' option also displays this information.

```
free blocks: 10 (2919 bytes)
       2280: 1
        508: 1
         76: 1
         32: 1
          7: 1
          4: 3
          3: 1
          1: 1
```

The next block of data shows a summary of all freed memory allocations. This is only possible because the 'NOFREE' option was also given, otherwise there would be no details on freed memory allocations. All of these entries show where the allocation was freed, which can be useful if you quickly needed to see where an allocation was freed. The 'SHOWFREED' option also displays this information. Note that the list will be limited to the size of the freed queue and will show only the most recently-freed items.

As this example was run on UNIX, the mpatrol library replaces the default implementations of `malloc()`, `free()`, etc. As can be seen below, this allows the library to trace all calls to allocate dynamic memory in a process, even from functions that were not compiled with mpatrol. Four of the five functions shown below were called by the mpatrol library in order to read the symbols from ELF object files. However, they are located in the ELF access library which was not compiled with mpatrol.

Note that the following data has again been cut down in size for the purposes of this example. The '`...`' marks text that has been removed.

```
freed allocations: 13 (19756 bytes)
    0x0002E010 (232 bytes) {free:1:0} [-|-|-]
        0x7FB3E5BC _elf_end+776
        0x7FB6B3D4 __mp_addsymbols+440
        0x7FB6FF5C __mp_init+208
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    0x0002E118 (3536 bytes) {free:2:0} [-|-|-]
        0x7FB3E450 _elf_end+412
        0x7FB6B3D4 __mp_addsymbols+440
        0x7FB6FF5C __mp_init+208
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    0x0002EF08 (232 bytes) {free:3:0} [-|-|-]
        0x7FB3E5BC _elf_end+776
        0x7FB6B3D4 __mp_addsymbols+440
        0x7FB6B4B4 __mp_addextsymbols+208
        0x7FB6FF64 __mp_init+216
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    0x0002F010 (2448 bytes) {free:4:0} [-|-|-]
        0x7FB3E450 _elf_end+412
        0x7FB6B3D4 __mp_addsymbols+440
        0x7FB6B4B4 __mp_addextsymbols+208
        0x7FB6FF64 __mp_init+216
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    ...

    0x00045DF0 (4 bytes) {free:20:0} [main|test.c|17]
        0x00010A14 main+132
        0x00010970 _start+192
```

The final block of data shows a summary of all unfreed memory allocations. This can show up memory leaks, although all but one of the unfreed memory allocations in this example come from the standard C library. On systems such as UNIX it does not really matter about these unfreed allocations since they will automatically be returned to the system on process termination.

However, the other unfreed allocation shows an example of a memory leak, where no pointers referencing that allocation remain in the program to free it with. If this was within a loop then the program could quickly run away with memory, causing at least a decrease in performance, and at most a memory shortage. The mpatrol library makes it easier to spot memory leaks, especially if the 'PROF' profiling option is used.

The 'SHOWUNFREED' option also displays this information.

```
unfreed allocations: 7 (1369 bytes)
    0x0002FDE0 (36 bytes) {calloc:13:0} [-|-|-]
        0x7FA54B7C _tzload+56
        0x7FA53990 _ltzset_u+444
        0x7FA52D98 localtime_u+28
        0x7FA3AF20 ctime+12
        0x7FB6D05C __mp_printversion+184
        0x7FB6FFA0 __mp_init+276
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    0x0002FE28 (241 bytes) {calloc:15:0} [-|-|-]
        0x7FA54E3C _tzload+760
        0x7FA53990 _ltzset_u+444
        0x7FA52D98 localtime_u+28
        0x7FA3AF20 ctime+12
        0x7FB6D05C __mp_printversion+184
        0x7FB6FFA0 __mp_init+276
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    0x0002FF40 (84 bytes) {calloc:16:0} [-|-|-]
        0x7FA54E64 _tzload+800
        0x7FA53990 _ltzset_u+444
        0x7FA52D98 localtime_u+28
        0x7FA3AF20 ctime+12
        0x7FB6D05C __mp_printversion+184
        0x7FB6FFA0 __mp_init+276
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
        0x00010970 _start+192

    0x0002FFB8 (13 bytes) {calloc:17:0} [-|-|-]
        0x7FA54EE8 _tzload+932
        0x7FA53990 _ltzset_u+444
        0x7FA52D98 localtime_u+28
        0x7FA3AF20 ctime+12
        0x7FB6D05C __mp_printversion+184
        0x7FB6FFA0 __mp_init+276
        0x7FB701FC __mp_alloc+84
        0x000109B8 main+40
```

```
    0x00010970 _start+192

0x0002FFE8 (4 bytes) {malloc:19:0} [main|test.c|14]
    0x000109B8 main+40
    0x00010970 _start+192

...
```

13 Tutorial

In this chapter we'll look at a real example of using the mpatrol library to debug a program. All of the following building and debugging steps were performed on an Intel Linux machine so the details may differ slightly on your system, but the concepts should remain the same. However, on systems without virtual memory some of the steps may actually cause the machine to lock up or crash so be aware of this if you are running such a system — you may be safer just reading this tutorial rather than attempting it!

This tutorial will also make use of the option '`USEDEBUG`' which displays source-level file names and line numbers associated with symbols in call stack tracebacks, but only if the underlying object file access library supports reading line tables from object files and even then only if the object files were compiled with debugging information enabled. Alternatively, you may be able to use the `mpsym` command to obtain such information instead.

The program we are going to look at is a simple filter which processes its standard input and displays the processed information on its standard output. In this case the program converts all lowercase characters to uppercase and removes any blank lines. The source for the program is given below, but can also be found in '`tests/tutorial/test1.c`'.

```
/*
 * Reads the standard input file stream, converts all lowercase
 * characters to uppercase, and displays all non-empty lines to the
 * standard output file stream.
 */


#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <ctype.h>


char *strtoupper(char *s)
{
    char *t;
    size_t i, l;

    l = strlen(s);
    t = (char *) malloc(l);
    for (i = 0; i < l; i++)
        t[i] = toupper(s[i]);
    t[i] = '\0';
    return t;
}


int main(void)
{
    char *b, *s;

    b = (char *) malloc(BUFSIZ);
    while (gets(b))
    {
```

```
57          s = strtoupper(b);
58          if (*s != '\0')
59          {
60              puts(s);
61              free(s);
62          }
63      }
64      free(b);
65      return EXIT_SUCCESS;
66  }
```

If you quickly skimmed over the above code then you might have noticed some rather obvious errors, but there are also some less obvious ones hidden there as well. After compiling and linking with the system C compiler and libraries it successfully runs, even when its source code is piped to it. So if it runs, why bother trying to debug it?

The short answer to that is that this program does in fact contain one rather major error that is likely to prevent it from running portably on other systems. However, for the purposes of this tutorial, we'll pretend that we've just been handed the source code for this program and have not worked on it before. So let's now try to compile and link it with the mpatrol library[1].

First, add the inclusion of '`mpatrol.h`' to line 34 so that we can replace calls to `malloc()` and `free()` with their mpatrol equivalents[2]. Then, recompile the program and link it with the mpatrol library. This time, running it with the '`CHECK=-`' option and even the simplest of non-empty input lines should cause it to abort!

If you look at the '`mpatrol.log`' file produced, you should see something along the lines of the following at the end of the log file.

```
ERROR: [FRECOR]: free memory corruption at 0x08067FF6
        0x08067FF6  00555555 55555555 5555              .UUUUUUUUU
```

This tells us that something has written a zero byte into free memory at location '`0x08067FF6`'. Unfortunately, the library only caught it at the next call to one of its functions so it had already happened somewhere in between the last call and the current call. Turning on the '`LOGALL`' option in the `MPATROL_OPTIONS` environment variable allows us to see the last successful function call to the mpatrol library.

```
ALLOC: malloc (56, 8192 bytes, 4 bytes) [main|test1.c|54]
        0x0804960E main+34 at test1.c:54
        0x4007C9CB __libc_start_main+255
        0x080494D1 _start+33

returns 0x080F0B48

ALLOC: malloc (68, 2 bytes, 4 bytes) [strtoupper|test1.c|42]
        0x08049592 strtoupper+50 at test1.c:42
        0x08049631 main+69 at test1.c:57
        0x4007C9CB __libc_start_main+255
        0x080494D1 _start+33

returns 0x08067FF4
```

[1] On UNIX systems with dynamic linking it might also be possible to run the program under the `mpatrol` command with its '`--dynamic`' option without having to recompile or relink, but compiling and linking with the mpatrol library is a more generic solution across different platforms.

[2] This is not strictly necessary on UNIX and Windows platforms (and AmigaOS when using `gcc`), but it does give us more debugging information.

Unfortunately, this only tells us that the last successful mpatrol library function call was `malloc()` called from `strtoupper()`. If we add the option 'OFLOWSIZE=8' to the MPATROL_OPTIONS environment variable then we get slightly more information about which memory allocation was affected[3].

```
ERROR: [ALLOVF]: allocation 0x08071E34 has a corrupted overflow buffer at
                 0x08071E36
        0x08071E36  00AAAAAA AAAAAAAA                    ........

    0x08071E34 (2 bytes) {malloc:68:0} [strtoupper|test1.c|42]
        0x08049592 strtoupper+50 at test1.c:42
        0x08049631 main+69 at test1.c:57
        0x4007C9CB __libc_start_main+255
        0x080494D1 _start+33
```

Now we can make a better guess about what is happening. Since the start of the upper overflow buffer of allocation 68 has been written to, we can assume that something has written one byte beyond the end of that memory allocation. You can probably see where that is happening now by looking at the code, but let's try to be even more sure that this is what is wrong.

The only foolproof way to do this is to add a watch point to keep an eye on the address that is being written to. This can normally only be done within a debugger, but on systems that support programmable software watch points, the 'OFLOWWATCH' option can be used to do the same thing. For the sake of generality, we'll use the debugger watch point approach, in this case with gdb. In order for the following example to work correctly you'll need to add the 'ALLOCSTOP=68' option to the MPATROL_OPTIONS environment variable so that we can stop just after the last successful memory allocation.

```
(gdb) break main
Breakpoint 1 at 0x80495f2: file test1.c, line 54.
(gdb) run <test1.c
Starting program: a.out
Breakpoint 1, main() at test1.c:54
54          b = (char *) malloc(BUFSIZ);
(gdb) break __mp_trap
Breakpoint 2 at 0x804f083
(gdb) continue
Continuing.
Breakpoint 2, 0x804f083 in __mp_trap()
(gdb) backtrace
#0  0x804f083 in __mp_trap()
#1  0x804c81b in __mp_getmemory()
#2  0x8049a94 in __mp_alloc()
#3  0x8049592 in strtoupper(s=0x80f0be0 "/*") at test1.c:42
#4  0x8049631 in main() at test1.c:57
(gdb) step
Single stepping until exit from function __mp_trap,
which has no line number information.
0x804c81b in __mp_getmemory()
(gdb) step
Single stepping until exit from function __mp_getmemory,
which has no line number information.
0x8049a94 in __mp_alloc()
```

[3] Note that the start address of the allocation has changed slightly since we added padding around it with the 'OFLOWSIZE' option.

```
(gdb) step
Single stepping until exit from function __mp_alloc,
which has no line number information.
strtoupper(s=0x80f0be0 "/*") at test1.c:43
43          for (i = 0; i < l; i++)
(gdb) watch *0x8071e36
Hardware watchpoint 3: *134684214
(gdb) continue
Continuing.
Hardware watchpoint 3: *134684214
Old value = -1431655766
New value = -1431655936
strtoupper(s=0x80f0be0 "/*") at test1.c:46
46          return t;
(gdb) quit
The program is running.  Exit anyway? (y or n) y
```

After loading the program into `gdb`, we need to break at `main()` so that we can run to a point where all of the shared library symbols have been loaded into memory[4]. We can then set another breakpoint at `__mp_trap()` and continue until allocation 68 has been reached.

Because the mpatrol library has not been built with debugging information in this example we can quickly step back to the `strtoupper()` function since `gdb` won't step through functions that have no debugging information. We then set a watch point on address '`0x8071e36`', which is the address of the memory location that has been causing the problems. After continuing, the debugger stops at line 46, but this is more likely to be line 45 since that is where a zero byte is being written to[5].

So, we have located the problem, which is simply a case of not allocating enough memory to contain the copied string *and* the terminating zero byte. We can also improve the `strtoupper()` function by checking the pointer returned by `malloc()` to see if it is '`NULL`', and if so simply exit with an error. You can try running the program with the '`FAILFREQ`' option to see how it would originally behave in a low memory situation.

The following listing shows the above modifications that we have made to our program. It can also be found in '`tests/tutorial/test2.c`'.

```
/*
 * Reads the standard input file stream, converts all lowercase
 * characters to uppercase, and displays all non-empty lines to the
 * standard output file stream.
 */


#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <ctype.h>
#include "mpatrol.h"


char *strtoupper(char *s)
```

[4] This is really only necessary when the mpatrol library has been built as a shared library.

[5] This is not necessarily the fault of the debugger or the debugging information generated by the compiler since on most platforms such watch points can only be caught after they occur, hence most debuggers show the next statement to be executed rather than the current one.

```
{
    char *t;
    size_t i, l;

    l = strlen(s);
    if ((t = (char *) malloc(l + 1)) == NULL)
    {
        fputs("strtoupper: out of memory\n", stderr);
        exit(EXIT_FAILURE);
    }
    for (i = 0; i < l; i++)
        t[i] = toupper(s[i]);
    t[i] = '\0';
    return t;
}


int main(void)
{
    char *b, *s;

    b = (char *) malloc(BUFSIZ);
    while (gets(b))
    {
        s = strtoupper(b);
        if (*s != '\0')
        {
            puts(s);
            free(s);
        }
    }
    free(b);
    return EXIT_SUCCESS;
}
```

Leaving aside the obvious problem with `gets()` and the general inefficiency of the algorithm, we could assume that our program works safely now and we can release it to the outside world. However, a user soon reports a problem with our program steadily using more and more memory during its execution when processing very large files.

This is generally attributable to a memory leak and so we can use the '`SHOWUNFREED`' option to try to detect where the memory leak is coming from. Following is some example output from the mpatrol log file when our program is run and is given a relatively small text file as input.

```
unfreed allocations: 10 (185 bytes)
    0x08062000 (176 bytes) {malloc:1:0} [-|-|-]
        0x400B681B _IO_new_fopen+27
        0x0804F24E __mp_openlogfile+70
        0x080497B5 __mp_init+109
        0x08049973 __mp_alloc+31
        0x0804962E main+34 at test2.c:59
        0x4007C9CB __libc_start_main+255
        0x080494D1 _start+33
```

```
0x08067FF4 (1 byte) {malloc:83:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x08067FF8 (1 byte) {malloc:89:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x08067FFC (1 byte) {malloc:90:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x0808B304 (1 byte) {malloc:95:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x0808B308 (1 byte) {malloc:96:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x0808B30C (1 byte) {malloc:101:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x0808B310 (1 byte) {malloc:113:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x0808B314 (1 byte) {malloc:114:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
    0x4007C9CB __libc_start_main+255
    0x080494D1 _start+33

0x0808B318 (1 byte) {malloc:118:0} [strtoupper|test2.c|43]
    0x08049593 strtoupper+51 at test2.c:43
    0x08049651 main+69 at test2.c:62
```

```
          0x4007C9CB __libc_start_main+255
          0x080494D1 _start+33
```

We can discount the first entry since that is obviously coming from when the mpatrol library first initialises itself. However, all of the other entries appear to be coming from line 43 within `strtoupper()` and appear to be only 1 byte in length. At that point in the code, the only possible reason for allocating 1 byte is when the string is empty and so that must mean that we are not freeing memory that contains empty strings. Looking at line 66 we can see that `free()` is only ever called for non-empty strings and therefore if we move the call to `free()` outside the test for an empty string we will fix the memory leak. The file '`tests/tutorial/test3.c`' contains the source for the final program.

Appendix A Functions

The mpatrol library contains implementations of dynamic memory allocation functions for C and C++ suitable for tracing and debugging. The library is intended to be used without requiring any changes to existing user source code except the inclusion of the 'mpatrol.h' header file, although additional functions are supplied for extra tracing and control. Note that the current version of the mpatrol library is contained in the MPATROL_VERSION preprocessor macro.

All of the function definitions in 'mpatrol.h' can be disabled by defining the NDEBUG preprocessor macro, which is the same macro used to control the behaviour of the assert() function. If NDEBUG is defined then no macro redefinition of functions will take place and all special mpatrol library functions will evaluate to empty statements. The 'mpalloc.h' header file will also be included in this case. It is intended that the NDEBUG preprocessor macro be defined in release builds.

The MP_MALLOC() family of functions that are defined in 'mpalloc.h' are also defined in 'mpatrol.h' when NDEBUG is not defined. The mpatrol versions of these functions contain more debugging information than the mpalloc versions do, but they do not call the allocation failure handler when no more memory is available (they cause the 'OUTMEM' error message to be given instead).

A.1 C dynamic memory allocation functions

The following 19 functions are available as replacements for existing C library functions. To use these you must include 'mpatrol.h' before all other header files, although on UNIX and Windows platforms (and AmigaOS when using gcc) they will be used anyway, albeit with slightly less tracing information. If alloca() is being used and 'alloca.h' is included then 'mpatrol.h' must appear before 'alloca.h' otherwise the debugging version of alloca() will not be used.

`void *malloc(size_t size)`
: Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *size* is '0' then the memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then the 'NULL' pointer will be returned and errno will be set to ENOMEM. The allocated memory must be deallocated with free() or reallocated with realloc().

`void *calloc(size_t nelem, size_t size)`
: Allocates *nelem* elements of *size* zero-initialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to nelem * size bytes in length. If nelem * size is '0' then the amount of memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then the 'NULL' pointer will be returned and errno will be set to ENOMEM. The allocated memory must be deallocated with free() or reallocated with realloc().

`void *memalign(size_t align, size_t size)`
: Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be aligned to *align* bytes and can be used to store data of up to *size* bytes in length. If *align* is zero then the default system alignment will be used. If *align* is not a power of two then it will be rounded up to the nearest power of two. If *align* is greater than the system page size then it will be truncated to that value. If *size* is '0' then the memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then

the 'NULL' pointer will be returned and errno will be set to ENOMEM. The allocated memory must be deallocated with free() or reallocated with realloc(), although the latter will not guarantee the preservation of alignment.

`void *valloc(size_t size)`
: Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be aligned to the system page size and can be used to store data of up to *size* bytes in length. If *size* is '0' then the memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then the 'NULL' pointer will be returned and errno will be set to ENOMEM. The allocated memory must be deallocated with free() or reallocated with realloc(), although the latter will not guarantee the preservation of alignment.

`void *pvalloc(size_t size)`
: Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be aligned to the system page size and can be used to store data of up to *size* bytes in length. If *size* is '0' then the memory allocated will be implicitly rounded up to '1' page, otherwise *size* will be implicitly rounded up to a multiple of the system page size. If there is not enough space in the heap then the 'NULL' pointer will be returned and errno will be set to ENOMEM. The allocated memory must be deallocated with free() or reallocated with realloc(), although the latter will not guarantee the preservation of alignment.

`void *alloca(size_t size)`
: Allocates *size* temporary uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *size* is '0' then the memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then the program will be terminated and the 'OUTMEM' error will be given. The alloca() function normally allocates its memory from the stack, with the result that all such allocations will be freed when the function returns. This version of alloca() allocates its memory from the heap in order to provide better debugging, but the allocations may not necessarily be freed immediately when the function returns. The allocated memory can be deallocated explicitly with dealloca(), but may not be reallocated or deallocated in any other way. This function is available for backwards compatibility with older C source code and should not be used in new code.

`char *strdup(const char *str)`
: Allocates exactly enough memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If *str* is 'NULL' then an error will be given and the 'NULL' pointer will be returned. If there is not enough space in the heap then the 'NULL' pointer will be returned and errno will be set to ENOMEM. The allocated memory must be deallocated with free() or reallocated with realloc().

`char *strndup(const char *str, size_t size)`
: Allocates exactly enough memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If *str* is 'NULL' and *size* is non-zero then an error will be given and the 'NULL' pointer will be returned. If the length of *str* is greater than *size* then only *size* characters will be allocated and copied, with one additional byte for the nul character. If there is not enough space in the heap then the 'NULL' pointer will be returned and errno

will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` or reallocated with `realloc()`. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`char *strsave(const char *str)`
: Allocates exactly enough memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If *str* is '`NULL`' then an error will be given and the '`NULL`' pointer will be returned. If there is not enough space in the heap then the '`NULL`' pointer will be returned and `errno` will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` or reallocated with `realloc()`. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`char *strnsave(const char *str, size_t size)`
: Allocates exactly enough memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If *str* is '`NULL`' and *size* is non-zero then an error will be given and the '`NULL`' pointer will be returned. If the length of *str* is greater than *size* then only *size* characters will be allocated and copied, with one additional byte for the nul character. If there is not enough space in the heap then the '`NULL`' pointer will be returned and `errno` will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` or reallocated with `realloc()`. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`char *strdupa(const char *str)`
: Allocates exactly enough temporary memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If *str* is '`NULL`' then an error will be given and the '`NULL`' pointer will be returned. If there is not enough space in the heap then the program will be terminated and the '`OUTMEM`' error will be given. The `strdupa()` function normally allocates its memory from the stack, with the result that all such allocations will be freed when the function returns. This version of `strdupa()` allocates its memory from the heap in order to provide better debugging, but the allocations may not necessarily be freed immediately when the function returns. The allocated memory can be deallocated explicitly with `dealloca()`, but may not be reallocated or deallocated in any other way. This function is available for backwards compatibility with older C source code and should not be used in new code.

`char *strndupa(const char *str, size_t size)`
: Allocates exactly enough temporary memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If *str* is '`NULL`' and *size* is non-zero then an error will be given and the '`NULL`' pointer will be returned. If the length of *str* is greater than *size* then only *size* characters will be allocated and copied, with one additional byte for the nul character. If there is not enough space in the heap then the program will be terminated and the '`OUTMEM`' error will be given. The `strndupa()` function normally allocates its memory from the stack, with the result that all such allocations will be freed when the function returns. This version of `strndupa()` allocates its memory

from the heap in order to provide better debugging, but the allocations may not necessarily be freed immediately when the function returns. The allocated memory can be deallocated explicitly with `dealloca()`, but may not be reallocated or deallocated in any other way. This function is available for backwards compatibility with older C source code and should not be used in new code.

`void *realloc(void *ptr, size_t size)`
: Resizes the memory allocation beginning at *ptr* to *size* bytes and returns a pointer to the first byte of the new allocation after copying *ptr* to the newly-allocated memory, which will be truncated if *size* is smaller than the original allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *ptr* is '`NULL`' then the call will be equivalent to `malloc()`. If *size* is '`0`' then the existing memory allocation will be freed and the '`NULL`' pointer will be returned. If *size* is greater than the original allocation then the extra space will be filled with uninitialised bytes. If there is not enough space in the heap then the '`NULL`' pointer will be returned and `errno` will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` and can be reallocated again with `realloc()`.

`void *reallocf(void *ptr, size_t size)`
: Resizes the memory allocation beginning at *ptr* to *size* bytes and returns a pointer to the first byte of the new allocation after copying *ptr* to the newly-allocated memory, which will be truncated if *size* is smaller than the original allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *ptr* is '`NULL`' then the call will be equivalent to `malloc()`. If *size* is '`0`' then the existing memory allocation will be freed and the '`NULL`' pointer will be returned. If *size* is greater than the original allocation then the extra space will be filled with uninitialised bytes. If there is not enough space in the heap then the '`NULL`' pointer will be returned, the original allocation will be freed and `errno` will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` and can be reallocated again with `realloc()`. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`void *recalloc(void *ptr, size_t nelem, size_t size)`
: Resizes the memory allocation beginning at *ptr* to *nelem* elements of *size* bytes and returns a pointer to the first byte of the new allocation after copying *ptr* to the newly-allocated memory, which will be truncated if `nelem * size` is smaller than the original allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to `nelem * size` bytes in length. If *ptr* is '`NULL`' then the call will be equivalent to `calloc()`. If `nelem * size` is '`0`' then the existing memory allocation will be freed and the '`NULL`' pointer will be returned. If `nelem * size` is greater than the original allocation then the extra space will be filled with zero-initialised bytes. If there is not enough space in the heap then the '`NULL`' pointer will be returned and `errno` will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` and can be reallocated again with `realloc()`. This function is available for backwards compatibility with older C libraries and `calloc()` and should not be used in new code.

`void *expand(void *ptr, size_t size)`
: Attempts to resize the memory allocation beginning at *ptr* to *size* bytes and either returns *ptr* if there was enough space to resize it, or '`NULL`' if the block could not be resized for a particular reason. If *ptr* is '`NULL`' then the call will be equivalent to `malloc()`. If *size* is '`0`' then the existing memory allocation will be freed and the '`NULL`' pointer will be returned. If *size* is greater than the original allocation then the extra space will be filled with uninitialised bytes and if *size* is less than the original allocation then the memory block will be truncated. If there is not

enough space in the heap then the 'NULL' pointer will be returned and `errno` will be set to `ENOMEM`. The allocated memory must be deallocated with `free()` and can be reallocated again with `realloc()`. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`void free(void *ptr)`
: Frees the memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory. If *ptr* is 'NULL' then no memory will be freed. All of the previous contents will be destroyed.

`void cfree(void *ptr, size_t nelem, size_t size)`
: Frees the memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory. If *ptr* is 'NULL' then no memory will be freed. All of the previous contents will be destroyed. The *nelem* and *size* parameters are ignored in this implementation. This function is available for backwards compatibility with older C libraries and `calloc()` and should not be used in new code.

`void dealloca(void *ptr)`
: Explicitly frees the temporary memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory. If *ptr* is 'NULL' then no memory will be freed. All of the previous contents will be destroyed. This function can only be used to free memory that was allocated with the `alloca()`, `strdupa()` and `strndupa()` functions, but is only really required if the mpatrol library does not automatically free such memory allocations when the allocating function returns. This function is mpatrol-specific and should not be used in release code.

A.2 C dynamic memory extension functions

The following 5 functions are available as replacements for existing C library extension functions that always abort and never return 'NULL' if there is insufficient memory to fulfil a request. To use these you must include 'mpatrol.h' before all other header files, although on UNIX and Windows platforms (and AmigaOS when using `gcc`) they will be used anyway, albeit with slightly less tracing information.

`void *xmalloc(size_t size)`
: Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *size* is '0' then the memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then the program will be terminated and the 'OUTMEM' error will be given. The allocated memory must be deallocated with `xfree()` or reallocated with `xrealloc()`.

`void *xcalloc(size_t nelem, size_t size)`
: Allocates *nelem* elements of *size* zero-initialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to `nelem * size` bytes in length. If `nelem * size` is '0' then the amount of memory allocated will be implicitly rounded up to '1' byte. If there is not enough space in the heap then the program will be terminated and the 'OUTMEM' error will be given. The allocated memory must be deallocated with `xfree()` or reallocated with `xrealloc()`.

`char *xstrdup(const char *str)`
: Allocates exactly enough memory from the heap to duplicate *str* (including the terminating nul character) and returns a pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no

alignment constraints and can be used to store character data up to the length of *str*. If *str* is 'NULL' then an error will be given and the 'NULL' pointer will be returned. If there is not enough space in the heap then the program will be terminated and the 'OUTMEM' error will be given. The allocated memory must be deallocated with `xfree()` or reallocated with `xrealloc()`.

`void *xrealloc(void *ptr, size_t size)`

Resizes the memory allocation beginning at *ptr* to *size* bytes and returns a pointer to the first byte of the new allocation after copying *ptr* to the newly-allocated memory, which will be truncated if *size* is smaller than the original allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *ptr* is 'NULL' then the call will be equivalent to `xmalloc()`. If *size* is '0' then it will be implicitly rounded up to '1'. If *size* is greater than the original allocation then the extra space will be filled with uninitialised bytes. If there is not enough space in the heap then the program will be terminated and the 'OUTMEM' error will be given. The allocated memory must be deallocated with `xfree()` and can be reallocated again with `xrealloc()`.

`void xfree(void *ptr)`

Frees the memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory. If *ptr* is 'NULL' then no memory will be freed. All of the previous contents will be destroyed.

A.3 C dynamic memory alternative functions

The following 6 functions are provided as convenient alternatives to the ANSI C dynamic memory allocation functions (although `strdup()` is not strictly an ANSI C function). They are implemented as preprocessor macro functions which may evaluate their arguments more than once, so extra care should be taken to avoid passing arguments with side-effects. None of the functions return 'NULL' if no memory is available and instead abort the program with a useful error message indicating where the call to allocate memory came from and what was being allocated. To use these you should include the 'mpatrol.h' or 'mpalloc.h' header files.

`void *MP_MALLOC(void *ptr, size_t count, typename type)`

Allocates *count* uninitialised items of type *type* from the heap, sets *ptr* to the result and returns a suitably-cast pointer to the first item of the allocation. The pointer returned will be suitably aligned for holding items of type *type*. If *count* is '0' then it will be implicitly rounded up to '1'. If there is not enough space in the heap then the program will be aborted after calling the allocation failure handler, which by default writes an appropriate error message to the standard error file stream. The allocated memory in *ptr* must be deallocated with `MP_FREE()` or reallocated with `MP_REALLOC()`.

`void *MP_CALLOC(void *ptr, size_t count, typename type)`

Allocates *count* zero-initialised items of type *type* from the heap, sets *ptr* to the result and returns a suitably-cast pointer to the first item of the allocation. The pointer returned will be suitably aligned for holding items of type *type*. If *count* is '0' then it will be implicitly rounded up to '1'. If there is not enough space in the heap then the program will be aborted after calling the allocation failure handler, which by default writes an appropriate error message to the standard error file stream. The allocated memory in *ptr* must be deallocated with `MP_FREE()` or reallocated with `MP_REALLOC()`.

`char *MP_STRDUP(char *ptr, const char *str)`

Allocates exactly enough memory from the heap to duplicate *str* (including the terminating nul character), sets *ptr* to the result and returns a suitably-cast pointer to the first byte of the allocation after copying *str* to the newly-allocated memory. The pointer returned will have no alignment constraints and can be used to store character data up to the length of *str*. If there is not enough space in the heap then the program will be aborted after calling the allocation failure handler, which by default writes an appropriate error message to the standard error file stream. The allocated memory in *ptr* must be deallocated with `MP_FREE()` or reallocated with `MP_REALLOC()`.

`void *MP_REALLOC(void *ptr, size_t count, typename type)`
Resizes the memory allocation beginning at *ptr* to *count* items of type *type* and returns a suitably-cast pointer to the first item of the new allocation after copying *ptr* to the newly-allocated memory, which will be truncated if *count* is smaller than the original number of items. The pointer returned will be suitably aligned for holding items of type *type*. If *ptr* is '`NULL`' then the call will be equivalent to `MP_MALLOC()`. If *count* is '`0`' then it will be implicitly rounded up to '`1`'. If *count* is greater than the original number of items then the extra space will be filled with uninitialised bytes. If there is not enough space in the heap then the program will be aborted after calling the allocation failure handler, which by default writes an appropriate error message to the standard error file stream. The allocated memory must be deallocated with `MP_FREE()` and can be reallocated again with `MP_REALLOC()`.

`void MP_FREE(void *ptr)`
Frees the memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory, and sets *ptr* to '`NULL`' after freeing the memory. If *ptr* is '`NULL`' then no memory will be freed.

`__mp_failhandler MP_FAILURE(__mp_failhandler func)`
Installs an allocation failure handler specifically for use with `MP_MALLOC()`, `MP_CALLOC()`, `MP_STRDUP()` and `MP_REALLOC()` and returns a pointer to the previously installed handler, normally the default handler if no handler had been previously installed. This will be called by the above functions when there is not enough space in the heap for them to satisfy their allocation request. The default allocation failure handler will terminate the program after writing an error message to the standard error file stream indicating where the original allocation request took place and what was being allocated.

A.4 C++ dynamic memory allocation functions

The following 5 functions are available as replacements for existing C++ library functions, but the replacements in '`mpatrol.h`' will only be used if the `MP_NOCPLUSPLUS` preprocessor macro is not defined. The replacement operators make use of the preprocessor in order to obtain source-level information. If this causes problems then you should define the `MP_NONEWDELETE` preprocessor macro and use the `MP_NEW`, `MP_NEW_NOTHROW` and `MP_DELETE` macros instead of `new` and `delete` directly. To use these C++ features you must include '`mpatrol.h`' before all other header files, although on UNIX and Windows platforms (and AmigaOS when using `gcc`) they will be used anyway, albeit with slightly less tracing information.

`void *operator new(size_t size)`
Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *size* is '`0`' then the memory allocated will be implicitly rounded up to '`1`' byte. If there is not enough space in the heap then either the `std::bad_alloc` exception will be thrown or the null pointer will be returned and `errno` will be set to `ENOMEM` — the behaviour depends on whether the *nothrow* version of the operator is used. The allocated memory must be deallocated with `operator delete`.

`void *operator new[](size_t size)`
: Allocates *size* uninitialised bytes from the heap and returns a pointer to the first byte of the allocation. The pointer returned will be suitably aligned for casting to any type and can be used to store data of up to *size* bytes in length. If *size* is '`0`' then the memory allocated will be implicitly rounded up to '`1`' byte. If there is not enough space in the heap then either the `std::bad_alloc` exception will be thrown or the null pointer will be returned and `errno` will be set to `ENOMEM` — the behaviour depends on whether the *nothrow* version of the operator is used. The allocated memory must be deallocated with `operator delete[]`.

`void operator delete(void *ptr)`
: Frees the memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory. If *ptr* is '`NULL`' then no memory will be freed. All of the previous contents will be destroyed. This function must only be used with memory allocated by `operator new`.

`void operator delete[](void *ptr)`
: Frees the memory allocation beginning at *ptr* so the memory can be reused by another call to allocate memory. If *ptr* is '`NULL`' then no memory will be freed. All of the previous contents will be destroyed. This function must only be used with memory allocated by `operator new[]`.

`void (*set_new_handler(void (*func)(void)))(void)`
: Installs a low-memory handler specifically for use with `operator new` and `operator new[]` and returns a pointer to the previously installed handler, or the null pointer if no handler had been previously installed. This will be called repeatedly by both functions when they would normally return '`NULL`', and this loop will continue until they manage to allocate the requested space. Note that this function is equivalent to `__mp_nomemory()` and will replace the handler installed by that function.

A.5 C memory operation functions

The following 10 functions are available as replacements for existing C library memory operation functions. To use these you must include '`mpatrol.h`' before all other header files, although on UNIX and Windows platforms (and AmigaOS when using `gcc`) they will be used anyway, albeit with slightly less tracing information.

`void *memset(void *ptr, int byte, size_t size)`
: Writes *size* bytes of value *byte* to the memory location beginning at *ptr* and returns *ptr*. If *size* is '`0`' then no bytes will be written. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be written.

`void bzero(void *ptr, size_t size)`
: Writes *size* zero bytes to the memory location beginning at *ptr*. If *size* is '`0`' then no bytes will be written. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be written. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`void *memccpy(void *dest, const void *src, int byte, size_t size)`
: Copies *size* bytes from *src* to *dest* and returns '`NULL`', or copies the number of bytes up to and including the first occurrence of *byte* if *byte* exists within the specified range and returns a pointer to the first byte after *byte*. If *size* is '`0`' or *src* is the same

as *dest* then no bytes will be copied. The source and destination ranges should not overlap, otherwise a warning will be written to the log file. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be copied.

`void *memcpy(void *dest, const void *src, size_t size)`
: Copies *size* bytes from *src* to *dest* and returns *dest*. If *size* is '`0`' or *src* is the same as *dest* then no bytes will be copied. The source and destination ranges should not overlap, otherwise a warning will be written to the log file. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be copied.

`void *memmove(void *dest, const void *src, size_t size)`
: Copies *size* bytes from *src* to *dest* and returns *dest*. If *size* is '`0`' or *src* is the same as *dest* then no bytes will be copied. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be copied.

`void bcopy(const void *src, void *dest, size_t size)`
: Copies *size* bytes from *src* to *dest*. If *size* is '`0`' or *src* is the same as *dest* then no bytes will be copied. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be copied. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`int memcmp(const void *ptr1, const void *ptr2, size_t size)`
: Compares *size* bytes from *ptr1* and *ptr2* and returns '`0`' if all of the bytes are identical, or returns the byte difference of the first differing bytes. If *size* is '`0`' or *ptr1* is the same as *ptr2* then no bytes will be compared. If the operation would read from an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be compared.

`int bcmp(const void *ptr1, const void *ptr2, size_t size)`
: Compares *size* bytes from *ptr1* and *ptr2* and returns '`0`' if all of the bytes are identical, or returns the byte difference of the first differing bytes. If *size* is '`0`' or *ptr1* is the same as *ptr2* then no bytes will be compared. If the operation would read from an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be compared. This function is available for backwards compatibility with older C libraries and should not be used in new code.

`void *memchr(const void *ptr, int byte, size_t size)`
: Searches up to *size* bytes in *ptr* for the first occurrence of *byte* and returns a pointer to it or '`NULL`' if no such byte occurs. If *size* is '`0`' then no bytes will be searched. If the operation would affect an existing memory allocation in the heap but would straddle that allocation's boundaries then an error message will be generated in the log file and no bytes will be searched.

`void *memmem(const void *ptr1, size_t size1, const void *ptr2, size_t size2)`
: Searches up to *size1* bytes in *ptr1* for the first occurrence of *ptr2* (which is exactly *size2* bytes in length) and returns a pointer to it or '`NULL`' if no such sequence of bytes occur. If *size1* or *size2* is '`0`' then no bytes will be searched. If the operation would affect an existing memory allocation in the heap but would straddle that

allocation's boundaries then an error message will be generated in the log file and no bytes will be searched.

A.6 mpatrol library functions

The following 24 functions are available as support routines for additional control and tracing in the mpatrol library. To use these you should include the '`mpatrol.h`' header file.

`unsigned long __mp_setoption(long opt, unsigned long val)`
: Sets the value of an mpatrol option after the library has been initialised. Options that require values are listed in '`mpatrol.h`' prefixed with '`MP_OPT_*`'. The *opt* argument should be set to one of these macros, and the *val* argument should be set to the option value, cast to an unsigned integer. The return value will be '`0`' on success and '`1`' on failure. Options that are flags are listed in '`mpatrol.h`' prefixed with '`MP_FLG_*`'. Multiple flags can be set or unset at once using the `MP_OPT_SETFLAGS` and `MP_OPT_UNSETFLAGS` options respectively, with the necessary flags specified in *val*. The return value will be '`0`' on success and a combination of all of the flags that could not be set or unset on failure.

`int __mp_getoption(long opt, unsigned long *val)`
: Gets the value of an mpatrol option after the library has been initialised. If *opt* is a valid option listed in '`mpatrol.h`' then '`1`' will be returned and the associated value will be returned in *val* and cast to an unsigned integer, otherwise '`0`' will be returned. If *opt* is `MP_OPT_SETFLAGS` then all of the mpatrol library flags that are set will be returned in *val*. If *opt* is `MP_OPT_UNSETFLAGS` then all of the mpatrol library flags that are not set will be returned in *val*.

`char *__mp_function(__mp_alloctype func)`
: Returns the name of the function corresponding to the allocation type *func* or '`NULL`' if no such allocation type exists.

`int __mp_setuser(const void *ptr, const void *data)`
: Sets the user data for the memory allocation containing *ptr*. The contents of *data* are entirely application-specific as user data will never be examined by the mpatrol library. Such data is associated with a memory allocation for its entire lifetime unless overridden by a subsequent call to `__mp_setuser()`. As such, the user data must be valid for the entire lifetime of the memory allocation, perhaps even after the allocation has been freed if the '`NOFREE`' option is being used. This function returns '`1`' if there is an allocated (or freed) memory block containing *ptr*, and '`0`' otherwise.

`int __mp_info(const void *ptr, __mp_allocinfo *info)`
: Obtains information about a specific memory allocation by placing statistics about *ptr* in *info*. If *ptr* does not belong to a previously allocated memory allocation then '`0`' will be returned, otherwise '`1`' will be returned and *info* will contain the following information:

Field	*Description*
`block`	Pointer to first byte of allocation.
`size`	Size of allocation in bytes.
`type`	Type of function which allocated memory.
`alloc`	Allocation index.
`realloc`	Number of times reallocated.
`thread`	Thread identifier.
`event`	Event of last modification.
`func`	Function in which allocation took place.

`file`	File in which allocation took place.
`line`	Line number at which allocation took place.
`stack`	Pointer to function call stack.
`typestr`	Type stored in allocation.
`typesize`	Size of type stored in allocation.
`userdata`	User data associated with allocation.
`freed`	Indicates if allocation has been freed.

`int __mp_syminfo(const void *ptr, __mp_symbolinfo *info)`

Obtains symbolic information about a specific code address by placing statistics about *ptr* in *info*. If *ptr* does not belong to a function symbol then '`0`' will be returned, otherwise '`1`' will be returned and *info* will contain the following information:

Field	*Description*
`name`	Name of symbol.
`object`	File containing symbol.
`addr`	Start address of symbol.
`size`	Size of symbol.
`file`	Filename corresponding to address.
`line`	Line number corresponding to address.

`int __mp_printinfo(const void *ptr)`

Displays information about a specific memory allocation containing *ptr* to the standard error file stream. If *ptr* does not belong to a previously allocated memory allocation then '`0`' will be returned, otherwise '`1`' will be returned. This function is intended to be called from within a debugger.

`unsigned long __mp_snapshot(void)`

Returns the current event number, effectively taking a snapshot of the heap. This number can then be used in later calls to `__mp_iterate()`.

`size_t __mp_iterate(int (*func)(const void *, void *), void *data, unsigned long event)`

Iterates over all of the current allocated and freed memory allocations, calling *func* with the start address of every memory allocation that has been modified since event number *event*. If *func* is '`NULL`' then `__mp_printinfo()` will be used as the callback function. If *event* is '`0`' then *func* will be called with the start address of every memory allocation. If *func* returns a negative number then the iteration process will be stopped immediately. If *func* returns a positive number above zero then `__mp_iterate()` will return the number of times *func* returned a non-zero number after the iteration process has stopped. The *data* argument is passed directly to *func* as its second argument and is not read by the mpatrol library.

`void __mp_memorymap(int stats)`

If *stats* is non-zero then the current statistics of the mpatrol library will be displayed. If the heap contains at least one allocated, freed or free block then a map of the current heap will also be displayed.

`void __mp_summary(void)`

Displays information about the current state of the mpatrol library, including its settings and any relevant statistics.

`int __mp_stats(__mp_heapinfo *info)`

Obtains statistics about the current state of the heap and places them in *info*. If this information could not be determined then '`0`' will be returned, otherwise '`1`' will be returned and *info* will contain the following information:

Field	*Description*

`acount`	Total number of allocated blocks.
`atotal`	Total size of allocated blocks.
`fcount`	Total number of free blocks.
`ftotal`	Total size of free blocks.
`gcount`	Total number of freed blocks.
`gtotal`	Total size of freed blocks.
`icount`	Total number of internal blocks.
`itotal`	Total size of internal blocks.

`void __mp_check(void)`

Forces the library to perform an immediate check of the overflow buffers of every memory allocation and to ensure that nothing has overwritten any free blocks. If any memory allocations made by the `alloca()` family of functions are out of scope then this function will also cause them to be freed.

`void (*__mp_prologue(void (*func)(const void *, size_t, const void *)))(const void *, size_t, const void *)`

Installs a prologue function to be called before any memory allocation, reallocation or deallocation function. This function will return a pointer to the previously installed prologue function, or the null pointer if no prologue function had been previously installed. The following arguments will be used to call the prologue function (including a third argument containing the return address of the calling function, or the null pointer if it cannot be determined):

Argument 1	*Argument 2*	*Called by*
`-1`	*size*	`malloc()`, etc.
ptr	*size*	`realloc()`, etc.
ptr	`-1`	`free()`, etc.
ptr	`-2`	`strdup()`, etc.

`void (*__mp_epilogue(void (*func)(const void *, const void *)))(const void *, const void *)`

Installs an epilogue function to be called after any memory allocation, reallocation or deallocation function. This function will return a pointer to the previously installed epilogue function, or the null pointer if no epilogue function had been previously installed. The following arguments will be used to call the epilogue function (including a second argument containing the return address of the calling function, or the null pointer if it cannot be determined):

Argument	*Called by*
ptr	`malloc()`, `realloc()`, `strdup()`, etc.
`-1`	`free()`, etc.

`void (*__mp_nomemory(void (*func)(void)))(void)`

Installs a low-memory handler and returns a pointer to the previously installed handler, or the '`NULL`' pointer if no handler had been previously installed. This will be called once by C memory allocation functions, and repeatedly by C++ memory allocation functions, when they would normally return '`NULL`'. Note that this function is equivalent to `set_new_handler()` and will replace the handler installed by that function.

`int __mp_printf(const char *fmt, ...)`

Writes format string *fmt* with variable arguments to the log file, with each line prefixed by '`>`'. The final length of the string that is written to the log file must not exceed 1024 characters. Returns the number of characters written, or a negative number upon error.

`int __mp_vprintf(const char *fmt, va_list args)`
: Writes format string *fmt* with variable argument list *args* to the log file, with each line prefixed by '`>`'. The final length of the string that is written to the log file must not exceed 1024 characters. Returns the number of characters written, or a negative number upon error.

`void __mp_logmemory(const void *ptr, size_t size)`
: Displays the contents of a block of memory beginning at *ptr*, dumping *size* consecutive bytes to the log file in hexadecimal format.

`int __mp_logstack(size_t frames)`
: Displays the current call stack, skipping *frames* stack frames from the current stack frame before writing the symbolic stack trace to the log file. Returns '`1`' if successful, or '`0`' if the call stack could not be determined or if *frames* was too large for the current call stack.

`int __mp_logaddr(const void *ptr)`
: Displays information about a specific memory allocation containing *ptr* to the log file. If *ptr* does not belong to a previously allocated memory allocation then '`0`' will be returned, otherwise '`1`' will be returned.

`int __mp_edit(const char *file, unsigned long line)`
: Invokes a text editor to edit *file* at line number *line* via the `mpedit` command. Returns '`1`' if the text editor was successfully invoked, '`-1`' if there was an error, or '`0`' if there is no support for this feature. This function will only work on a system where the '`EDIT`' option works.

`int __mp_list(const char *file, unsigned long line)`
: Displays a context listing of *file* at line number *line* via the `mpedit` command. Returns '`1`' if the listing was successfully performed, '`-1`' if there was an error, or '`0`' if there is no support for this feature. This function will only work on a system where the '`LIST`' option works.

`int __mp_view(const char *file, unsigned long line)`
: Either invokes a text editor to edit *file* at line number *line* or displays a context listing of *file* at line number *line* depending on the setting of the '`EDIT`' and '`LIST`' options. This is done via the `mpedit` command and will have no effect if the '`EDIT`' and '`LIST`' options are not set or if these options are not supported on the system. Returns '`1`' if the edit or listing was successfully performed, '`-1`' if there was an error, or '`0`' if neither of the options were set or if there is no support for this feature.

Appendix B Environment

The library can read certain options at run-time from an environment variable called `MPATROL_OPTIONS`. This variable must contain one or more valid option keywords from the list below and must be no longer than 1024 characters in length. If `MPATROL_OPTIONS` is unset or empty then the default settings will be used.

The syntax for options specified within the `MPATROL_OPTIONS` environment variable is '`OPTION`' or '`OPTION=VALUE`', where '`OPTION`' is a keyword from the list below and '`VALUE`' is the setting for that option. If '`VALUE`' is numeric then it may be specified using binary, octal, decimal or hexadecimal notation, with binary notation beginning with either '`0b`' or '`0B`'. If '`VALUE`' is a character string containing spaces then it may be quoted using double quotes. No whitespace may appear between the '`=`' sign, but whitespace must appear between different options. Note that option keywords can be given in lowercase as well as uppercase, or a mixture of both.

'`ALLOCBYTE`'=<*unsigned-integer*>
: Specifies an 8-bit byte pattern with which to prefill newly-allocated memory. This can be used to detect the use of memory which has not been initialised after allocation. Note that this setting will not affect memory allocated with `calloc()` or `recalloc()` as these functions always prefill allocated memory with an 8-bit byte pattern of zero. Default value: '`ALLOCBYTE=0xFF`'.

'`ALLOCSTOP`'=<*unsigned-integer*>
: Specifies an allocation index at which to stop the program when it is being allocated. When the number of memory allocations reaches this number the program will be halted, and its state may be examined at that point by using a suitable debugger. Note that this setting will be ignored if its value is zero. Default value: '`ALLOCSTOP=0`'.

'`ALLOWOFLOW`'
: Specifies that a warning rather than an error should be produced if any memory operation function overflows the boundaries of a memory allocation, and that the operation should still be performed. This option is provided for circumstances where it is desirable for the memory operation to be performed, regardless of whether it is erroneous or not.

'`AUTOSAVE`'=<*unsigned-integer*>
: Specifies the frequency at which to periodically write the profiling data to the profiling output file. When the total number of profiled memory allocations and deallocations is a multiple of this number then the current profiling information will be written to the profiling output file. This option can be used to instruct the mpatrol library to dump out any profiling information just before a fatal error occurs in a program, for example. Note that this setting will be ignored if its value is zero. Default value: '`AUTOSAVE=0`'.

'`CHECK`'=<*unsigned-range*>
: Specifies a range of allocation indices at which to check the integrity of free memory and overflow buffers. The range must be specified as no more than two unsigned integers separated by a dash, followed by an optional forward slash and an unsigned integer specifying an event checking frequency. If numbers on either the left side or the right side of the dash are omitted then they will be assumed to be '`0`' and *infinity* respectively. A value of '`0`' on its own indicates that no such checking will ever be performed. This option can be used to speed up the execution speed of the library at the expense of checking. Default value: '`CHECK=0`'.

'CHECKALL'
: Equivalent to the 'CHECKALLOCS', 'CHECKREALLOCS', 'CHECKFREES' and 'CHECKMEMORY' options specified together.

'CHECKALLOCS'
: Checks that no attempt is made to allocate a block of memory of size zero. A warning will be issued for every such case.

'CHECKFREES'
: Checks that no attempt is made to deallocate a 'NULL' pointer. A warning will be issued for every such case.

'CHECKMEMORY'
: Checks that no attempt is made to perform a zero-length memory operation on a 'NULL' pointer.

'CHECKREALLOCS'
: Checks that no attempt is made to reallocate a 'NULL' pointer or resize an existing block of memory to size zero. Warnings will be issued for every such case.

'DEFALIGN'=<*unsigned-integer*>
: Specifies the default alignment for general-purpose memory allocations, which must be a power of two (and will be rounded up to the nearest power of two if it is not). The default alignment for a particular system is calculated at run-time.

'EDIT'
: Specifies that a text editor should be invoked to edit any relevant source files that are associated with any warnings or errors when they occur. Only diagnostics which occur at source lines in the program will be affected and only then if they contain source-level information. This option is currently only available on UNIX platforms as it makes use of the `mpedit` command. It also overrides the behaviour of the 'LIST' option and affects the behaviour of the `__mp_view()` function.

'FAILFREQ'=<*unsigned-integer*>
: Specifies the frequency at which all memory allocations will randomly fail. For example, a value of '10' will mean that roughly 1 in 10 memory allocations will fail, but a value of '0' will disable all random failures. This option can be useful for stress-testing an application. Default value: 'FAILFREQ=0'.

'FAILSEED'=<*unsigned-integer*>
: Specifies the random number seed which will be used when determining which memory allocations will randomly fail. A value of '0' will instruct the library to pick a random seed every time it is run. Any other value will mean that the random failures will be the same every time the program is run, but only as long as the seed stays the same. Default value: 'FAILSEED=0'.

'FREEBYTE'=<*unsigned-integer*>
: Specifies an 8-bit byte pattern with which to prefill newly-freed memory. This can be used to detect the use of memory which has just been freed. It is also used internally to ensure that freed memory has not been overwritten. Note that the freed memory may be reused the next time a block of memory is allocated and so once memory has been freed its contents are not guaranteed to remain the same as the specified byte pattern. Default value: 'FREEBYTE=0x55'.

'FREESTOP'=<*unsigned-integer*>
: Specifies an allocation index at which to stop the program when it is being freed. When the memory allocation with the specified allocation index is to be freed the program will be halted, and its state may be examined at that point using a suitable debugger. Note that this setting will be ignored if its value is zero. Default value: 'FREESTOP=0'.

'HELP' Displays a quick-reference option summary to the stderr file stream.

'LARGEBOUND'=<*unsigned-integer*>
Specifies the limit in bytes up to which memory allocations should be classified as large allocations for profiling purposes. This limit must be greater than the small and medium bounds. Default value: 'LARGEBOUND=2048'.

'LIMIT'=<*unsigned-integer*>
Specifies the limit in bytes at which all memory allocations should fail if the total allocated memory should increase beyond this. This can be used to stress-test software to see how it behaves in low memory conditions. The internal memory used by the library itself will not be counted as part of the total heap size, but on some systems there may be a small amount of memory required to initialise the library itself. Note that this setting will be ignored if its value is zero. Default value: 'LIMIT=0'.

'LIST' Specifies that a context listing should be shown for any relevant source files that are associated with any warnings or errors when they occur. Only diagnostics which occur at source lines in the program will be affected and only then if they contain source-level information. This option is currently only available on UNIX platforms as it makes use of the mpedit command. It also overrides the behaviour of the 'EDIT' option and affects the behaviour of the __mp_view() function.

'LOGALL' Equivalent to the 'LOGALLOCS', 'LOGREALLOCS', 'LOGFREES' and 'LOGMEMORY' options specified together.

'LOGALLOCS'
Specifies that all memory allocations are to be logged and sent to the log file. Note that any memory allocations made internally by the library will not be logged.

'LOGFILE'=<*string*>
Specifies an alternative file in which to place all diagnostics from the mpatrol library. If the LOGDIR environment variable is set and the specified file does not contain a path component in its filename then the log file will be located in the directory specified in LOGDIR. A filename of 'stderr' will send all diagnostics to the stderr file stream and a filename of 'stdout' will do the equivalent with the stdout file stream. Note that if a problem occurs while opening the log file or if any diagnostics require to be displayed before the log file has had a chance to be opened then they will be sent to the stderr file stream. Default value: 'LOGFILE=mpatrol.log' or 'LOGFILE=%n.%p.log' if the LOGDIR environment variable is set.

'LOGFREES'
Specifies that all memory deallocations are to be logged and sent to the log file. Note that any memory deallocations made internally by the library will not be logged.

'LOGMEMORY'
Specifies that all memory operations are to be logged and sent to the log file. These operations will be made by calls to functions such as memset() and memcpy(). Note that any memory operations made internally by the library will not be logged.

'LOGREALLOCS'
Specifies that all memory reallocations are to be logged and sent to the log file. Note that any memory reallocations made internally by the library will not be logged.

'MEDIUMBOUND'=<*unsigned-integer*>
Specifies the limit in bytes up to which memory allocations should be classified as medium allocations for profiling purposes. This limit must be greater than the small bound but less than the large bound. Default value: 'MEDIUMBOUND=256'.

'NOFREE'=<*unsigned-integer*>
: Specifies that a number of recently-freed memory allocations should be prevented from being returned to the free memory pool. Such freed memory allocations will then be flagged as freed and can be used by the library to provide better diagnostics. If the size of the freed queue is specified as zero then all freed memory will be immediately reused by the mpatrol library. Note that if this option is given a non-zero value then the mpatrol library will always force a memory reallocation to return a pointer to newly-allocated memory, but the `expand()` function will never be affected by this option. Default value: '`NOFREE=0`'.

'NOPROTECT'
: Specifies that the mpatrol library's internal data structures should not be made read-only after every memory allocation reallocation or deallocation. This may significantly speed up execution but this will be at the expense of less safety if the program accidentally overwrites some of the library's internal data structures. Note that this option has no effect on systems that do not support memory protection.

'OFLOWBYTE'=<*unsigned-integer*>
: Specifies an 8-bit byte pattern with which to fill the overflow buffers of all memory allocations. This is used internally to ensure that nothing has been written beyond the beginning or the end of a block of allocated memory. Note that this setting will only have an effect if the '`OFLOWSIZE`' option is in use. Default value: '`OFLOWBYTE=0xAA`'.

'OFLOWSIZE'=<*unsigned-integer*>
: Specifies the size in bytes to use for all overflow buffers, which must be a power of two (and will be rounded up to the nearest power of two if it is not). This is used internally to ensure that nothing has been written beyond the beginning or the end of a block of allocated memory. Note that this setting specifies the size for only one of the overflow buffers given to each memory allocation; the other overflow buffer will have an identical size. No overflow buffers will be used if this setting is zero. Default value: '`OFLOWSIZE=0`'.

'OFLOWWATCH'
: Specifies that watch point areas should be used for overflow buffers rather than filling with the overflow byte. This can significantly reduce the speed of program execution. Note that this option has no effect on systems that do not support watch point areas.

'PAGEALLOC'=<'LOWER'|'UPPER'>
: Specifies that each individual memory allocation should occupy at least one page of virtual memory and should be placed at the lowest or highest point within these pages. This allows the library to place an overflow buffer of one page on either side of every memory allocation and write-protect these pages as well as all free and freed memory. Note that this option has no effect on systems that do not support memory protection, and is disabled by default on other systems as it can slow down the speed of program execution.

'PRESERVE'
: Specifies that any reallocated or freed memory allocations should preserve their original contents. This option must be used with the '`NOFREE`' option and has no effect otherwise.

'PROF'
: Specifies that all memory allocations and deallocations are to be profiled and sent to the profiling output file. Memory reallocations are treated as a memory deallocation immediately followed by a memory allocation.

'PROFFILE'=<*string*>
: Specifies an alternative file in which to place all memory allocation profiling information from the mpatrol library. If the `PROFDIR` environment variable is set and the specified file does not contain a path component in its filename then the profiling output file will be located in the directory specified in `PROFDIR`. A filename of '`stderr`' will send this information to the `stderr` file stream and a filename of '`stdout`' will do the equivalent with the `stdout` file stream. Note that if a problem occurs while opening the profiling output file then the profiling information will not be output. Default value: '`PROFFILE=mpatrol.out`' or '`PROFFILE=%n.%p.out`' if the `PROFDIR` environment variable is set.

'PROGFILE'=<*string*>
: Specifies an alternative filename with which to locate the executable file containing the program's symbols. On most systems, the library will automatically be able to determine this filename, but on a few systems this option may have to be used before any or all symbols can be read.

'REALLOCSTOP'=<*unsigned-integer*>
: Specifies a reallocation index at which to stop the program when a memory allocation is being reallocated. If the '`ALLOCSTOP`' option is non-zero then the program will be halted when the allocation matching that allocation index is reallocated the specified number of times. Otherwise the program will be halted the first time any allocation is reallocated the specified number of times. Note that this setting will be ignored if its value is zero. Default value: '`REALLOCSTOP=0`'.

'SAFESIGNALS'
: Instructs the library to save and replace certain signal handlers during the execution of library code and to restore them afterwards. This was the default behaviour in version 1.0 of the mpatrol library and was changed since some memory-intensive programs became very hard to interrupt using the keyboard, thus giving the impression that the program or system had hung.

'SHOWALL'
: Equivalent to the '`SHOWFREE`', '`SHOWFREED`', '`SHOWUNFREED`', '`SHOWMAP`' and '`SHOWSYMBOLS`' options specified together.

'SHOWFREE'
: Specifies that a summary of all of the free memory blocks should be displayed at the end of program execution. This step will not be performed if an abnormal termination occurs or if there were no free memory blocks.

'SHOWFREED'
: Specifies that a summary of all of the freed memory allocations should be displayed at the end of program execution. This option must be used in conjunction with the '`NOFREE`' option and this step will not be performed if an abnormal termination occurs or if there were no freed allocations.

'SHOWMAP'
: Specifies that a memory map of the entire heap should be displayed at the end of program execution. This step will not be performed if an abnormal termination occurs or if the heap is empty.

'SHOWSYMBOLS'
: Specifies that a summary of all of the function symbols read from the program's executable file should be displayed at the end of program execution. This step will not be performed if an abnormal termination occurs or if no symbols could be read from the executable file.

'SHOWUNFREED'
: Specifies that a summary of all of the unfreed memory allocations should be displayed at the end of program execution. This step will not be performed if an abnormal termination occurs or if there are no unfreed allocations.

'SMALLBOUND'=<*unsigned-integer*>
: Specifies the limit in bytes up to which memory allocations should be classified as small allocations for profiling purposes. This limit must be greater than zero but less than the medium and large bounds. Default value: 'SMALLBOUND=32'.

'TRACE'
: Specifies that all memory allocations and deallocations are to be traced and sent to the tracing output file. Memory reallocations are treated as a memory deallocation immediately followed by a memory allocation.

'TRACEFILE'=<*string*>
: Specifies an alternative file in which to place all memory allocation tracing information from the mpatrol library. If the `TRACEDIR` environment variable is set and the specified file does not contain a path component in its filename then the tracing output file will be located in the directory specified in `TRACEDIR`. A filename of '`stderr`' will send this information to the `stderr` file stream and a filename of '`stdout`' will do the equivalent with the `stdout` file stream. Note that if a problem occurs while opening the tracing output file then the tracing information will not be output. Default value: '`TRACEFILE=mpatrol.trace`' or '`TRACEFILE=%n.%p.trace`' if the `TRACEDIR` environment variable is set.

'UNFREEDABORT'=<*unsigned-integer*>
: Specifies the minimum number of unfreed allocations at which to abort the program just before program termination. A summary of all the allocations will be displayed on the standard error file stream before aborting. This option may be handy for use in batch tests as it can force tests to fail if they do not free up a minimum number of memory allocations. Note that this setting will be ignored if its value is zero. Default value: 'UNFREEDABORT=0'.

'USEDEBUG'
: Specifies that any debugging information in the executable file should be used to obtain additional source-level information. This option will only have an effect if the executable file contains a compiler-generated line number table and will be ignored if the mpatrol library was built to support an object file access library that cannot read line tables from object files. Note that this option will slow down program execution, use up more system memory and may leave unaccounted unfreed memory allocations at program termination.

'USEMMAP'
: Specifies that the library should use `mmap()` instead of `sbrk()` to allocate user memory on UNIX platforms. This option should be used if there are problems when using the mpatrol library in combination with another malloc library which uses `sbrk()` to allocate its memory. Memory internal to the mpatrol library is allocated with `mmap()` on systems where it is supported in order to segregate it from user memory, and this behaviour is reversed with the 'USEMMAP' option. It is ignored on systems that do not support the `mmap()` system call. Note that some UNIX systems require this option in order for the mpatrol library to be able to perform memory protection with the `mprotect()` system call.

Appendix C Options

A utility program called `mpatrol` is provided to run commands that have been linked with the mpatrol library.

```
mpatrol [options] <command> [arguments]
```

The `mpatrol` command is used to set various mpatrol library *options* when running *command* with its *arguments*. In most cases, *command* must have been linked with the mpatrol library, unless the '`--dynamic`' option is used in which case *command* need only have been dynamically linked.

All mpatrol library diagnostics are sent to the file '`mpatrol.%n.log`' in the current directory by default (where '`%n`' is the current process id) but this can be changed using the '`--log-file`' option. Similarly, the default profiling output filename is '`mpatrol.%n.out`' and the default tracing output filename is '`mpatrol.%n.trace`'.

Alternatively, the log file, profiling output file and tracing output file names can contain '`%p`', which will be replaced with the name of the program being executed without the directory components. If the executable filename could not be determined or was not set then it will be replaced with '`mpatrol`'. A similar replacement character sequence is '`%f`', which will be replaced by the pathname of the program being executed, with all path separation characters replaced by underscores.

The current date can be entered into such filenames through the use of the '`%d`' character sequence, which will be replaced with the date in the form '`YYYYMMDD`'. The current time can be added with '`%t`', which will be replaced with the time in the form '`HHMMSS`'. If the date or time could not be determined, these will be replaced with '`today`' and '`now`' respectively.

All of the following options (except '`--dynamic`', '`--help`', '`--show-env`', '`--threads`' and '`--version`') correspond to their listed mpatrol library option (see Appendix B [Environment], page 131). Note that some of these options have a one character equivalent option that can be used for brevity. The list of one character options can be viewed with the '`--help`' option or viewed in the UNIX manual pages. Such options are parsed on the command line in a similar way to the UNIX function `getopt()`.

'`--alloc-byte`' <*unsigned-integer*>
: ['`ALLOCBYTE`'] Specifies an 8-bit byte pattern with which to prefill newly-allocated memory.

'`--alloc-stop`' <*unsigned-integer*>
: ['`ALLOCSTOP`'] Specifies an allocation index at which to stop the program when it is being allocated.

'`--allow-oflow`'
: ['`ALLOWOFLOW`'] Specifies that a warning rather than an error should be produced if any memory operation function overflows the boundaries of a memory allocation, and that the operation should still be performed.

'`--auto-save`' <*unsigned-integer*>
: ['`AUTOSAVE`'] Specifies the frequency at which to periodically write the profiling data to the profiling output file.

'`--check`' <*unsigned-range*>
: ['`CHECK`'] Specifies a range of allocation indices at which to check the integrity of free memory and overflow buffers.

'`--check-all`'
: ['`CHECKALL`'] Equivalent to the '`--check-allocs`', '`--check-reallocs`', '`--check-frees`' and '`--check-memory`' options specified together.

'--check-allocs'
: ['CHECKALLOCS'] Checks that no attempt is made to allocate a block of memory of size zero.

'--check-frees'
: ['CHECKFREES'] Checks that no attempt is made to deallocate a NULL pointer.

'--check-memory'
: ['CHECKMEMORY'] Checks that no attempt is made to perform a zero-length memory operation on a NULL pointer.

'--check-reallocs'
: ['CHECKREALLOCS'] Checks that no attempt is made to reallocate a NULL pointer or resize an existing block of memory to size zero.

'--def-align' <*unsigned-integer*>
: ['DEFALIGN'] Specifies the default alignment for general-purpose memory allocations, which must be a power of two.

'--dynamic'
: Specifies that programs which were not linked with the mpatrol library should also be traced, but only if they were dynamically linked. This option will only work if the system dynamic linker has the ability to preload a set of user-specified shared libraries via a special environment variable.

'--edit'
: ['EDIT'] Specifies that a text editor should be invoked to edit any relevant source files that are associated with any warnings or errors when they occur.

'--fail-freq' <*unsigned-integer*>
: ['FAILFREQ'] Specifies the frequency at which all memory allocations will randomly fail.

'--fail-seed' <*unsigned-integer*>
: ['FAILSEED'] Specifies the random number seed which will be used when determining which memory allocations will randomly fail.

'--free-byte' <*unsigned-integer*>
: ['FREEBYTE'] Specifies an 8-bit byte pattern with which to prefill newly-freed memory.

'--free-stop' <*unsigned-integer*>
: ['FREESTOP'] Specifies an allocation index at which to stop the program when it is being freed.

'--help'
: Displays a quick-reference option summary.

'--large-bound' <*unsigned-integer*>
: ['LARGEBOUND'] Specifies the limit in bytes up to which memory allocations should be classified as large allocations for profiling purposes.

'--limit' <*unsigned-integer*>
: ['LIMIT'] Specifies the limit in bytes at which all memory allocations should fail if the total allocated memory should increase beyond this.

'--list'
: ['LIST'] Specifies that a context listing should be shown for any relevant source files that are associated with any warnings or errors when they occur.

'--log-all'
: ['LOGALL'] Equivalent to the '--log-allocs', '--log-reallocs', '--log-frees' and '--log-memory' options specified together.

'--log-allocs'
: ['LOGALLOCS'] Specifies that all memory allocations are to be logged and sent to the log file.

'--log-file' <*string*>
: ['LOGFILE'] Specifies an alternative file in which to place all diagnostics from the mpatrol library.

'--log-frees'
: ['LOGFREES'] Specifies that all memory deallocations are to be logged and sent to the log file.

'--log-memory'
: ['LOGMEMORY'] Specifies that all memory operations are to be logged and sent to the log file.

'--log-reallocs'
: ['LOGREALLOCS'] Specifies that all memory reallocations are to be logged and sent to the log file.

'--medium-bound' <*unsigned-integer*>
: ['MEDIUMBOUND'] Specifies the limit in bytes up to which memory allocations should be classified as medium allocations for profiling purposes.

'--no-free' <*unsigned-integer*>
: ['NOFREE'] Specifies that a number of recently-freed memory allocations should be prevented from being returned to the free memory pool.

'--no-protect'
: ['NOPROTECT'] Specifies that the mpatrol library's internal data structures should not be made read-only after every memory allocation, reallocation or deallocation.

'--oflow-byte' <*unsigned-integer*>
: ['OFLOWBYTE'] Specifies an 8-bit byte pattern with which to fill the overflow buffers of all memory allocations.

'--oflow-size' <*unsigned-integer*>
: ['OFLOWSIZE'] Specifies the size in bytes to use for all overflow buffers, which must be a power of two.

'--oflow-watch'
: ['OFLOWWATCH'] Specifies that watch point areas should be used for overflow buffers rather than filling with the overflow byte.

'--page-alloc-lower'
: ['PAGEALLOC=LOWER'] Specifies that each individual memory allocation should occupy at least one page of virtual memory and should be placed at the lowest point within these pages.

'--page-alloc-upper'
: ['PAGEALLOC=UPPER'] Specifies that each individual memory allocation should occupy at least one page of virtual memory and should be placed at the highest point within these pages.

'--preserve'
: ['PRESERVE'] Specifies that any reallocated or freed memory allocations should preserve their original contents.

'--prof'
: ['PROF'] Specifies that all memory allocations are to be profiled and sent to the profiling output file.

'--prof-file' <*string*>
: ['PROFFILE'] Specifies an alternative file in which to place all memory allocation profiling information from the mpatrol library.

'--prog-file' <*string*>
: ['PROGFILE'] Specifies an alternative filename with which to locate the executable file containing the program's symbols.

'--realloc-stop' <*unsigned-integer*>
: ['REALLOCSTOP'] Specifies an allocation index at which to stop the program when a memory allocation is being reallocated.

'--safe-signals'
: ['SAFESIGNALS'] Instructs the library to save and replace certain signal handlers during the execution of library code and to restore them afterwards.

'--show-all'
: ['SHOWALL'] Equivalent to the '--show-free', '--show-freed', '--show-unfreed', '--show-map' and '--show-symbols' options specified together.

'--show-env'
: Displays the contents of the MPATROL_OPTIONS environment variable. This will be shown after all of the other command line options have been processed and will prevent the specified command from being run.

'--show-free'
: ['SHOWFREE'] Specifies that a summary of all of the free memory blocks should be displayed at the end of program execution.

'--show-freed'
: ['SHOWFREED'] Specifies that a summary of all of the freed memory allocations should be displayed at the end of program execution.

'--show-map'
: ['SHOWMAP'] Specifies that a memory map of the entire heap should be displayed at the end of program execution.

'--show-symbols'
: ['SHOWSYMBOLS'] Specifies that a summary of all of the function symbols read from the program's executable file should be displayed at the end of program execution.

'--show-unfreed'
: ['SHOWUNFREED'] Specifies that a summary of all of the unfreed memory allocations should be displayed at the end of program execution.

'--small-bound' <*unsigned-integer*>
: ['SMALLBOUND'] Specifies the limit in bytes up to which memory allocations should be classified as small allocations for profiling purposes.

'--threads'
: Specifies that the program to be run is multithreaded if the '--dynamic' option is used. This option is required if the multithreaded version of the mpatrol library should be preloaded instead of the normal version.

'--trace'
: ['TRACE'] Specifies that all memory allocations are to be traced and sent to the tracing output file.

'--trace-file' <*string*>
: ['TRACEFILE'] Specifies an alternative file in which to place all memory allocation tracing information from the mpatrol library.

'--unfreed-abort' <*unsigned-integer*>
: ['UNFREEDABORT'] Specifies the minimum number of unfreed allocations at which to abort the program just before program termination.

'--use-debug'
: ['USEDEBUG'] Specifies that any debugging information in the executable file should be used to obtain additional source-level information.

'--use-mmap'
: ['USEMMAP'] Specifies that the library should use mmap() instead of sbrk() to allocate user memory.

'--version'
: Displays the version number of the mpatrol command.

Appendix D Diagnostic messages

The following table lists the warnings and errors that are likely to appear in the mpatrol log file when problems with dynamic memory allocations and memory operations occur. Other types of warnings and errors may also appear in the log file, but they are likely to be associated with parsing options and reading symbols from executable files and so should be self-explanatory.

In all cases, if a warning or error is caused by one of the memory access checking functions (invoked through the use of the '`-fcheck-memory-usage`' option to the GNU compiler) then execution will halt regardless, despite what the description of the diagnostic message says.

Note that on UNIX platforms, if the diagnostic message is caused by a line in the program source then the '`EDIT`' and '`LIST`' options can be used to illustrate more clearly where in the source code the warning or error occurred.

- '`ALLOVF`'

  Message '`allocation %1 has a corrupted overflow buffer at %2`'

  Type Error

  '`%1`' The pointer to the memory allocation that has a corrupted overflow buffer.

  '`%2`' The pointer to the first byte of corruption in the memory allocation's overflow buffer.

  Cause Something has corrupted the overflow buffer of a memory allocation and this has been caught at the next invocation of an mpatrol function when the '`OFLOWSIZE`' or '`PAGEALLOC`' options were used. This particular error message will not occur if the '`OFLOWWATCH`' option was used since all overflow buffers will be write protected.

  Additional

  The library summary, the contents of the overflow buffer and information about the original memory allocation.

  Result Execution terminates.

- '`ALLZER`'

  Message '`attempt to create an allocation of size 0`'

  Type Warning

  Cause A function was called to allocate memory with a size of '`0`' when either of the '`CHECKALL`' or '`CHECKALLOCS`' options were used. This warning will not occur by default as the ANSI C/C++ standards allow this behaviour, and it is really only a portability issue.

  Additional

  The log file entry.

  Result The size is increased to 1 byte and execution continues.

- '`BADALN`'

  Message '`alignment %1 is not a power of two`'

  Type Warning

  '`%1`' The alignment in bytes.

  Cause The `memalign()` function was called to allocate memory with an alignment which was not a power of two when either of the '`CHECKALL`' or '`CHECKALLOCS`' options were used.

Additional
: The log file entry.

Result
: The alignment is rounded up to the nearest power of two and execution continues.

- ‘FRDCOR’

  Message: ‘freed allocation %1 has memory corruption at %2’

  Type: Error

  ‘%1’: The pointer to the freed memory allocation that has been corrupted.

  ‘%2’: The pointer to the first byte of corruption in the freed memory allocation.

  Cause: Something has corrupted the contents of a previously freed memory allocation and this has been caught at the next invocation of an mpatrol function when the ‘NOFREE’ option was used. This particular error message will not occur if the ‘PAGEALLOC’ option was used since all freed memory allocations will be write protected and will also not occur if the ‘PRESERVE’ option was used since the free byte cannot be used to verify the freed allocation’s contents.

  Additional: The library summary, the contents of the freed memory block and information about the original memory allocation.

  Result: Execution terminates.

- ‘FRDOPN’

  Message: ‘attempt to perform operation on freed memory’

  Type: Error

  Cause: A memory operation function was called to operate on a previously freed memory allocation when the ‘NOFREE’ option was used.

  Additional: Information about the original memory allocation.

  Result: The memory operation fails and execution continues.

- ‘FRDOVF’

  Message: ‘freed allocation %1 has a corrupted overflow buffer at %2’

  Type: Error

  ‘%1’: The pointer to the freed memory allocation that has a corrupted overflow buffer.

  ‘%2’: The pointer to the first byte of corruption in the freed memory allocation’s overflow buffer.

  Cause: Something has corrupted the overflow buffer of a previously freed memory allocation and this has been caught at the next invocation of an mpatrol function when the ‘NOFREE’ option was used in conjunction with the ‘OFLOWSIZE’ or ‘PAGEALLOC’ options. This particular error message will not occur if the ‘OFLOWWATCH’ option was used since all overflow buffers will be write protected.

  Additional: The library summary, the contents of the overflow buffer and information about the original memory allocation.

  Result: Execution terminates.

- ‘FRECOR’

  Message ‘free memory corruption at %1’

  Type Error

  ‘%1’ The pointer to the first byte of corruption in free memory.

  Cause Something has corrupted the contents of the free memory pool and this has been caught at the next invocation of an mpatrol function. This particular error message will not occur if the ‘PAGEALLOC’ option was used since all free memory will be write protected.

  Additional
  The library summary and the contents of the free memory block.

  Result Execution terminates.

- ‘FRENUL’

  Message ‘attempt to free a NULL pointer’

  Type Warning

  Cause A function was called to free an existing memory allocation with a pointer of ‘NULL’ when either of the ‘CHECKALL’ or ‘CHECKFREES’ options were used. This warning will not occur by default as the ANSI C/C++ standards allow this behaviour, and it is really only a portability issue.

  Additional
  The log file entry.

  Result No memory allocation will be freed and execution continues.

- ‘FREOPN’

  Message ‘attempt to perform operation on free memory’

  Type Error

  Cause A memory operation function was called to operate on free memory.

  Additional
  No additional information.

  Result The memory operation fails and execution continues.

- ‘ILLMEM’

  Message ‘illegal memory access at address %1’

  Type Error

  ‘%1’ The address at which the illegal memory access occurred.

  Cause An attempt was made to read from or write to an illegal address on systems which have virtual memory. This address may or may not exist in the heap, or it may be a perfectly valid address that was misaligned and caused a bus error. In either case, the mpatrol library will attempt to associate the address with an existing memory allocation. This error may also appear instead of memory corruption errors if the ‘PAGEALLOC’ or ‘OFLOWWATCH’ options were used.

  Additional
  The library summary, information about the original memory allocation (if possible) and the call stack of where the error occurred.

Result Execution terminates.

- '`INCOMP`'

  Message '`%1 was allocated with %2`'

  Type Error

  '`%1`' The pointer to the memory allocation that is to be resized or freed.

  '`%2`' The name of the function which originally allocated the memory allocation.

  Cause A function was called to resize or free a memory allocation that was allocated with a function that is incompatible with the current request. For example, a memory allocation which was allocated with `operator new` being resized with `realloc()`.

  Additional
  The log file entry and information about the original memory allocation.

  Result The reallocation or deallocation fails and execution continues.

- '`MAXALN`'

  Message '`alignment %1 is greater than the system page size`'

  Type Warning

  '`%1`' The alignment in bytes.

  Cause The `memalign()` function was called to allocate memory with an alignment which was greater than the system page size when either of the '`CHECKALL`' or '`CHECKALLOCS`' options were used. The mpatrol library cannot currently align memory allocations to a byte alignment over this limit, but then neither can most other implementations.

  Additional
  The log file entry.

  Result The alignment is set to the system page size and execution continues.

- '`MISMAT`'

  Message '`%1 does not match allocation of %2`'

  Type Error

  '`%1`' The pointer to the memory allocation that is to be resized or freed.

  '`%2`' The pointer to the memory allocation that the mpatrol library knows about.

  Cause A function was called to resize or free a memory allocation that begins at a different address from that supplied.

  Additional
  The log file entry and information about the original memory allocation.

  Result The reallocation or deallocation fails and execution continues.

- '`NOTALL`'

  Message '`%1 has not been allocated`'

  Type Error

  '`%1`' The pointer to the memory allocation that is to be resized or freed.

Cause A function was called to resize or free a memory allocation that has not been allocated. It may be that the memory allocation has just been freed, in which case the 'NOFREE' option should be used to provide a better diagnostic message.

Additional
The log file entry.

Result The reallocation or deallocation fails and execution continues.

- 'NULOPN'

  Message 'attempt to perform operation on a NULL pointer'

  Type Error

  Cause A memory operation function was called to operate on a 'NULL' pointer. If the length of the operation was zero then this error will only occur when the 'CHECKALL' or 'CHECKMEMORY' options were used as the ANSI C/C++ standards allow this behaviour, and it is really only a portability issue.

  Additional
  No additional information.

  Result The memory operation fails and execution continues.

- 'OUTMEM'

  Message 'out of memory'

  Type Error

  Cause The `alloca()`, `xmalloc()` or `MP_MALLOC()` families of functions were called to allocate memory, but no more memory was available to allocate and the low-memory handler, if installed, could not free up sufficient memory. This error can also be caused by a call to the `operator new` or `operator new[]` C++ operators (not the *nothrow* versions) when they would otherwise return a 'NULL' pointer and the mpatrol library was compiled with a C compiler (which means that it cannot throw a `std::bad_alloc` exception).

  Additional
  The library summary.

  Result Execution terminates.

- 'PRVFRD'

  Message '%1 was freed with %2'

  Type Error

  '%1' The pointer to the memory allocation that is to be resized or freed.

  '%2' The name of the function which originally freed the memory allocation.

  Cause A function was called to resize or free a memory allocation that had previously been freed when the 'NOFREE' option was used.

  Additional
  The log file entry and information about the original memory allocation.

  Result The reallocation or deallocation fails and execution continues.

- 'RNGOVF'

  Message 'range [%1,%2] overflows [%3,%4]'

Type Warning/Error

'%1' The start address of the memory region.

'%2' The end address of the memory region.

'%3' The start address of the memory allocation.

'%4' The end address of the memory allocation.

Cause A memory operation function was called to operate on a range of memory which overflowed the boundaries of a memory allocation.

Additional
Information about the original memory allocation.

Result The operation will be only be performed (and will be changed from an error to a warning) if the '`ALLOWOFLOW`' option was used, but execution will continue regardless.

- '`RNGOVL`'

  Message '`range [%1,%2] overlaps [%3,%4]`'

  Type Warning

  '%1' The start address of the source memory region.

  '%2' The end address of the source memory region.

  '%3' The start address of the destination memory region.

  '%4' The end address of the destination memory region.

  Cause The `memcpy()` or `memccpy()` function was called to copy overlapping memory regions. This is an error on many systems and the ANSI C/C++ standards specify that `memmove()` should be used instead.

  Additional
  The log file entry.

  Result The copy operation will still be performed but it will deal correctly with overlapping memory regions.

- '`RSZNUL`'

  Message '`attempt to resize a NULL pointer`'

  Type Warning

  Cause A function was called to resize an existing memory allocation with a pointer of '`NULL`' when either of the '`CHECKALL`' or '`CHECKREALLOCS`' options were used. This warning will not occur by default as the ANSI C/C++ standards allow this behaviour, and it is really only a portability issue.

  Additional
  The log file entry.

  Result A new memory allocation is returned and execution continues.

- '`RSZZER`'

  Message '`attempt to resize an allocation to size 0`'

  Type Warning

Cause A function was called to resize an existing memory allocation to a size of '0' when either of the 'CHECKALL' or 'CHECKREALLOCS' options were used. This warning will not occur by default as the ANSI C/C++ standards allow this behaviour, and it is really only a portability issue.

Additional
The log file entry.

Result The existing memory allocation will be freed and execution continues.

- 'STROVF'

Message 'string %1 overflows [%2,%3]'

Type Error

'%1' The start address of the string.

'%2' The start address of the memory allocation.

'%3' The end address of the memory allocation.

Cause A string function was called to operate on a string which overflowed the boundaries of a memory allocation.

Additional
Information about the original memory allocation.

Result The operation will not be performed and execution continues.

- 'ZERALN'

Message 'alignment 0 is invalid'

Type Warning

Cause The memalign() function was called to allocate memory with an alignment of '0' when either of the 'CHECKALL' or 'CHECKALLOCS' options were used.

Additional
The log file entry.

Result The alignment is set to the default system alignment and execution continues.

Appendix E Library performance

The following times were obtained on a Sun Ultra 5 with an UltraSPARC IIi processor running at 333MHz and running Solaris 7. The test performed was the one in '`tests/pass/test1.c`' and all tests were run on a lightly loaded system, but were run several times to obtain an average result. Obviously, these times can only be an approximation, but should serve to illustrate the effects on performance that each option can have. All times are given in seconds, and the second time on each line was obtained with the same options plus the '`NOPROTECT`' option. The tests were all run with the '`CHECK=-`' option, so running with the '`CHECK=0`' option would speed things up dramatically, albeit at the expense of less error checking.

Running with basic options:

no options	0.618	0.258
'`OFLOWSIZE=2`'	0.645	0.296
'`OFLOWSIZE=8`'	0.686	0.327
'`PAGEALLOC=LOWER`'	7.785	7.372
'`PAGEALLOC=UPPER`'	7.821	7.469

Running when all freed memory allocations are kept:

'`NOFREE=0xFFFF`'	0.943	0.506
'`NOFREE=0xFFFF OFLOWSIZE=2`'	1.026	0.579
'`NOFREE=0xFFFF OFLOWSIZE=8`'	1.091	0.645
'`NOFREE=0xFFFF PAGEALLOC=LOWER`'	8.013	7.598
'`NOFREE=0xFFFF PAGEALLOC=UPPER`'	8.026	7.616

Running when all freed memory allocations are kept and their contents are preserved:

'`NOFREE=0xFFFF PRESERVE`'	0.719	0.292
'`NOFREE=0xFFFF PRESERVE OFLOWSIZE=2`'	0.792	0.367
'`NOFREE=0xFFFF PRESERVE OFLOWSIZE=8`'	0.850	0.419
'`NOFREE=0xFFFF PRESERVE PAGEALLOC=LOWER`'	8.043	7.616
'`NOFREE=0xFFFF PRESERVE PAGEALLOC=UPPER`'	8.052	7.631

Running using watch points to check the overflow buffers:

'`OFLOWSIZE=2 OFLOWWATCH`'	Interrupted after half an hour as it still hadn't finished.

Running using the Solaris malloc libraries:

Solaris malloc(3c) library	0.033
Solaris malloc(3x) library	0.036
Solaris bsdmalloc(3x) library	0.028
Solaris mapmalloc(3x) library	0.033
Solaris watchmalloc(3x) library	40.845

Appendix F File formats

The formats of the profiling and tracing output files that are produced by the mpatrol library are described here[1].

F.1 Profiling file format

Every mpatrol profiling output file contains the following components.

- 4 bytes containing the characters '`M`', '`P`', '`T`' and '`L`'.
- 1 unsigned integer representing the value '`1`'. This is used by `mprof` to determine the endianness of the processor that produced the profiling output file so that it can decide whether to perform byte-swapping on the input data.
- 1 unsigned integer containing the version number of the mpatrol library which produced the profiling output file.
- 3 unsigned integers containing the small, medium and large allocation bounds.
- 1 unsigned integer containing the allocation bin size. If the allocation bin size is greater than zero then it is followed by the allocation bins, the large allocation totals, the deallocation bins and the large deallocation totals, where the bins are arrays of unsigned integers with dimensions of the allocation bin size and the totals are unsigned integers.
- 1 unsigned integer containing the number of profiling data structures. If the number of profiling data structures is greater than zero then it is followed by the profiling data structures themselves, which are of the following structure.
  - 1 unsigned integer representing the index of this profiling data.
  - 4 unsigned integers representing the small, medium, large and extra large allocation counts for this profiling data.
  - 4 unsigned integers representing the small, medium, large and extra large allocation totals for this profiling data.
  - 4 unsigned integers representing the small, medium, large and extra large deallocation counts for this profiling data.
  - 4 unsigned integers representing the small, medium, large and extra large deallocation totals for this profiling data.
- 1 unsigned integer containing the number of call sites. If the number of call sites is greater than zero then it is followed by the call sites themselves, which are of the following structure.
  - 1 unsigned integer representing the index of this call site.
  - 1 unsigned integer representing the index of the parent call site.
  - 1 generic pointer representing the code address of this call site.
  - 1 unsigned integer representing the index of an associated symbol.
  - 1 unsigned integer representing the offset of the symbol name.
  - 1 unsigned integer representing the index of any associated profiling data.
- 1 unsigned integer containing the number of symbol addresses. If the number of symbol addresses is greater than zero then it is followed by the symbol addresses themselves, which are generic pointers.
- 1 unsigned integer containing the size of the symbol name string table. This is followed by the symbol name string table, which is an array of characters containing the nul-terminated symbol names.
- 4 bytes containing the characters '`M`', '`P`', '`T`' and '`L`'.

[1] The file '`extra/magic`' contains a UNIX *magic* file excerpt for automatically identifying an mpatrol log file, an mpatrol profiling output file and an mpatrol tracing output file with the `file` command.

F.2 Tracing file format

Every mpatrol tracing output file contains the following components.

- 4 bytes containing the characters '`M`', '`T`', '`R`' and '`C`'.
- 1 unsigned integer representing the value '`1`'. This is used by `mptrace` to determine the endianness of the processor that produced the tracing output file so that it can decide whether to perform byte-swapping on the input data.
- 1 unsigned integer containing the version number of the mpatrol library which produced the tracing output file.
- One or more of the following event records.
  - If the event is a system heap allocation for use by the mpatrol library's internal data structures then the event record will begin with the character '`I`' followed by the start address and size in bytes of the heap allocation encoded as unsigned LEB128 numbers.
  - If the event is a system heap allocation for use by the program's memory allocations then the event record will begin with the character '`H`' followed by the start address and size in bytes of the heap allocation encoded as unsigned LEB128 numbers.
  - If the event is a memory allocation then the event record will begin with the character '`A`' followed by the allocation index, start address and size in bytes of the memory allocation encoded as unsigned LEB128 numbers.
  - If the event is a memory deallocation then the event record will begin with the character '`F`' followed by the allocation index of the memory allocation encoded as an unsigned LEB128 number.
- 4 bytes containing the characters '`M`', '`T`', '`R`' and '`C`'.

Appendix G Supported systems

Following is a list of systems on which the mpatrol library has been built and tested. The system details include the operating system and version, the processor type, the object file format and the compiler used to compile the library and tests. The details following each system list any features of the library that are not (or cannot be) supported on that system.

- AIX 4.1, IBM RS/6000, XCOFF, `cc`
  - The thread-safe version of the library does not work.
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.
  - There is a problem obtaining the program's executable filename when using the shared library version of mpatrol.
  - The shared library version of mpatrol does not currently override the dynamic memory allocation functions that are called from other shared libraries and so will only affect object files that are statically linked. If this is a problem then should link your programs with the following additional compiler options in order to perform a static link instead of a dynamic link: '`-bnoautoimp`' '`-bimport:/lib/syscalls.exp`' and also '`-bimport:/lib/threads.exp`' if linking with '`libmpatrolmt.a`'.
  - A makefile called '`Makefile.aix`' is supplied in '`build/unix`' which will build the mpatrol library as an AIX shared library. The shared library will be embedded within the mpatrol archive library as is done with the system libraries.
  - The '`--dynamic`' option to the `mpatrol` command has no effect.
- DG/UX 4.11, Intel Pentium Pro, ELF32, `gcc`
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.
  - The '`--dynamic`' option to the `mpatrol` command has no effect.
- DG/UX 4.20MU07, Intel Pentium Pro, ELF32, `gcc`
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.
  - The '`--dynamic`' option to the `mpatrol` command does not work unless '`libelf.so`' is available.
- DG/UX 4.11, Motorola 88100, ELF32, `gcc`
  - The thread-safe version of the library does not work if the mpatrol library is built as a shared library.
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.
  - Call stack traversal only works with unoptimised code.
  - The '`--dynamic`' option to the `mpatrol` command has no effect.
- DRS/NX 6.2, SPARC V7, ELF32, `cc`
  - The option '`-DSYSTEM=SYSTEM_DRSNX`' must be added to the `CFLAGS` section in the '`Makefile`' before building the library.
  - The thread-safe version of the library does not work. This is because there does not appear to be any evidence that this version of the operating system supports threads.
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.

  - The '`--dynamic`' option to the `mpatrol` command has no effect.

- DYNIX/ptx 4.5, Intel Pentium Pro, ELF32, `cc`
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.
  - The '`--dynamic`' option to the `mpatrol` command does not work unless '`libelf.so`' is available.

- FreeBSD 4.2, Intel Celeron, ELF32, `gcc`
  - The '`OFLOWWATCH`' option has no effect.
  - The '`USEDEBUG`' option has no effect.
  - The '`LIST`' option does not work since the '`--listing`' option does not work in the `mpedit` command.
  - On ELF-based systems, the mpatrol library requires either the ELF access library or the GNU BFD library to be installed on the system, otherwise no symbols can be read from executable files or shared libraries and the library must be built with the '`-DFORMAT=FORMAT_NONE`' option. No such extra libraries are required on '`a.out`'-based systems.
  - The '`--dynamic`' option to the `mpatrol` command does not appear to work correctly, giving spurious errors in the log file.
  - The `mpedit` command does not support the '`--listing`' option due to the lack of an `nl` command on the system.

- HP/UX 10.20, HP PA/RISC 9000, BFD, `gcc`
  - The thread-safe version of the library does not work. This is because there does not appear to be any evidence that this version of the operating system supports threads.
  - The '`OFLOWWATCH`' option has no effect.
  - The '`--dynamic`' option to the `mpatrol` command has no effect.

- IRIX 5.3, MIPS R4000, ELF32, `cc`
  - The thread-safe version of the library does not work. This is because there does not appear to be any evidence that this version of the operating system supports threads.
  - This version of the operating system only allows up to 100 user-programmable software watch points, which means that the '`OFLOWWATCH`' option will not work properly if more than 50 memory allocations exist at one time.
  - The '`USEDEBUG`' option has no effect.
  - Stack traversal may be unreliable from signal-handlers.

- Red Hat Linux 6.0, Intel Pentium III, BFD, `g++`
  - The '`OFLOWWATCH`' option has no effect.
  - The '`--dynamic`' option to the `mpatrol` command does not work unless '`libiberty.so`' is available.
- Red Hat Linux 6.1, Intel Pentium III, BFD, `g++`
  - The thread-safe version of the library does not work due to the system threads library calling `malloc()` and `bzero()` recursively.
  - The '`OFLOWWATCH`' option has no effect.
  - The '`--dynamic`' option to the `mpatrol` command does not work unless '`libiberty.so`' is available.
- Red Hat Linux 6.2, Intel Pentium III, BFD, `g++`

- The 'OFLOWWATCH' option has no effect.
- The '--dynamic' option to the mpatrol command does not work unless 'libiberty.so' is available.

- Red Hat Linux 5.1, Motorola 68040, BFD, gcc
  - The thread-safe version of the library does not work due to the system threads library calling malloc() and bzero() recursively.
  - The 'OFLOWWATCH' option has no effect.
  - The '--dynamic' option to the mpatrol command does not work unless 'libiberty.so' is available.
- Red Hat Linux 5.1, Motorola 68040, ELF32, gcc
  - The thread-safe version of the library does not work due to the system threads library calling malloc() and bzero() recursively.
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - The '--dynamic' option to the mpatrol command does not work unless 'libelf.so' is available.

- LynxOS 3.0.0, Intel Pentium Pro, BFD, gcc
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEMMAP' option has no effect.
  - The 'LIST' option does not work since the '--listing' option does not work in the mpedit command.
  - There is currently no support for reading symbols from COFF shared libraries. You should currently always perform a static link instead of a dynamic link when linking your program, but that is the default on LynxOS anyway.
  - The '--dynamic' option to the mpatrol command has no effect.
  - The mpsym command does not work if perl is not installed due to the lack of a printf command on the system.
  - The mpedit command does not support the '--listing' option due to the lack of an nl command on the system.
- LynxOS 3.0.0, Intel Pentium Pro, COFF, gcc
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - The 'USEMMAP' option has no effect.
  - The 'LIST' option does not work since the '--listing' option does not work in the mpedit command.
  - There is currently no support for reading symbols from COFF shared libraries. You should currently always perform a static link instead of a dynamic link when linking your program, but that is the default on LynxOS anyway.
  - The '--dynamic' option to the mpatrol command has no effect.
  - The mpsym command does not work if perl is not installed due to the lack of a printf command on the system.
  - The mpedit command does not support the '--listing' option due to the lack of an nl command on the system.

- LynxOS 3.0.0, PowerPC, BFD, gcc
  - The 'OFLOWWATCH' option has no effect.

  - The 'USEMMAP' option has no effect.
  - The 'LIST' option does not work since the '--listing' option does not work in the mpedit command.
  - There is currently no support for reading symbols from XCOFF shared libraries. You should currently always perform a static link instead of a dynamic link when linking your program, but that is the default on LynxOS anyway.
  - The '--dynamic' option to the mpatrol command has no effect.
  - The mpsym command does not work if perl is not installed due to the lack of a printf command on the system.
  - The mpedit command does not support the '--listing' option due to the lack of an nl command on the system.
- LynxOS 3.0.0, PowerPC, XCOFF, gcc
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - The 'USEMMAP' option has no effect.
  - The 'LIST' option does not work since the '--listing' option does not work in the mpedit command.
  - There is currently no support for reading symbols from XCOFF shared libraries. You should currently always perform a static link instead of a dynamic link when linking your program, but that is the default on LynxOS anyway.
  - The '--dynamic' option to the mpatrol command has no effect.
  - The mpsym command does not work if perl is not installed due to the lack of a printf command on the system.
  - The mpedit command does not support the '--listing' option due to the lack of an nl command on the system.
- SINIX 5.43, MIPS R4000, ELF32, cc
  - The thread-safe version of the library does not work. This is because there does not appear to be any evidence that this version of the operating system supports threads.
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - Stack traversal may be unreliable from signal-handlers.
  - The '--dynamic' option to the mpatrol command has no effect.
- Solaris 2.6, Intel Pentium Pro, BFD, gcc
  - No known issues.
- Solaris 2.6, Intel Pentium Pro, ELF32, gcc
  - The 'USEDEBUG' option has no effect.
- Solaris 2.5, SPARC V8, BFD, gcc
  - The thread-safe version of the library does not work due to a problem with a system library.
  - The 'OFLOWWATCH' option has no effect. The '-DMP_PROCFS_SUPPORT=0' and '-DMP_WATCH_SUPPORT=0' options must be added to CFLAGS in the 'Makefile'.
- Solaris 2.5, SPARC V8, ELF32, gcc
  - The thread-safe version of the library does not work due to a problem with a system library.
  - The 'OFLOWWATCH' option has no effect. The '-DMP_PROCFS_SUPPORT=0' and '-DMP_WATCH_SUPPORT=0' options must be added to CFLAGS in the 'Makefile'.

- The 'USEDEBUG' option has no effect.
- Solaris 7, SPARC V9, BFD, g++
  - The mpatrol library can be compiled and run in a 64-bit environment.
- Solaris 7, SPARC V9, ELF32/ELF64, g++
  - The 'USEDEBUG' option has no effect.
  - The mpatrol library can be compiled and run in a 64-bit environment.
- Solaris 8, SPARC V9, BFD, g++
  - The mpatrol library can be compiled and run in a 64-bit environment.
- Solaris 8, SPARC V9, ELF32/ELF64, g++
  - The 'USEDEBUG' option has no effect.
  - The mpatrol library can be compiled and run in a 64-bit environment.

- UnixWare 7.1.1, Intel Pentium II, ELF32, gcc
  - The option '-DSYSTEM=SYSTEM_UNIXWARE' must be added to the CFLAGS section in the 'Makefile' before building the library.
  - The thread-safe version of the library does not work.
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - The '--dynamic' option to the mpatrol command has no effect.

- AmigaOS 3.1, Motorola 68040, BFD, gcc
  - No memory protection so the 'PAGEALLOC' option has no effect.
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - The 'USEMMAP' option has no effect.
  - The 'EDIT' and 'LIST' options have no effect.
  - Limited support for call stack traversal.
  - Limited support for reading symbols.
  - No detection of illegal memory accesses.
  - The '--dynamic' option to the mpatrol command has no effect.
  - The mptrace command has no GUI.
  - The mpsym and hexwords commands do not work unless gdb and the GNU text processing tools are installed.
  - The mpedit command does not work.
- AmigaOS 3.1, Motorola 68040, n/a, SAS/C
  - No automatic override of malloc(), etc., without inclusion of 'mpatrol.h'.
  - No memory protection so the 'PAGEALLOC' option has no effect.
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEDEBUG' option has no effect.
  - The 'USEMMAP' option has no effect.
  - The 'EDIT' and 'LIST' options have no effect.
  - No support for call stack traversal.
  - No support for reading symbols.
  - No detection of illegal memory accesses.
  - The '--dynamic' option to the mpatrol command has no effect.

  - The mptrace command has no GUI.
  - The mpsym, mpedit and hexwords commands do not work.

- Microsoft Windows NT 4.0, Intel Pentium III, PE, Microsoft Visual C++
  - The 'OFLOWWATCH' option has no effect.
  - The 'USEMMAP' option has no effect.
  - The 'EDIT' and 'LIST' options have no effect.
  - There is currently a problem when mixing the archive library version of mpatrol with the DLL version of the Microsoft Runtime Library, and vice versa.
  - The '--dynamic' option to the mpatrol command has no effect.
  - The mptrace command has no GUI.
  - The mpsym, mpedit and hexwords commands do not work.

G.1 Adding a new operating system

- Add a new TARGET and/or SYSTEM definition in 'target.h'. The TARGET macro is for fundamentally different operating systems, whereas the SYSTEM macro is for differentiating variations of a particular operating system.
- Make any necessary modifications to 'config.h'.
- Add any support for memory allocation in 'memory.c'.
- Add any support for stack traversal in 'stack.c'.
- Add any platform-specific assembler code in 'machine.c'.
- Add any support for signals in 'signals.c'.
- Add any support for threads in 'mutex.c'.
- Add any support for filenames in 'diag.c'.
- Add a new version and date format (or use an existing one) in 'version.c'.
- Decide if the malloc() replacements should be used from 'malloc.c'.
- Add any support for invoking commands in 'mpatrol.c'.
- Add a new subdirectory in the 'build' directory that contains a 'Makefile' and any other files that are required to build the library on the new operating system.

G.2 Adding a new processor architecture

- Add a new ARCH and/or ENVIRON definition in 'target.h'. The ARCH macro specifies a processor family, whereas the ENVIRON macro specifies the size of a word if the processor family can support different word sizes.
- Make any necessary modifications to 'config.h'.
- Add any support for memory allocation in 'memory.c'.
- Add any support for stack traversal in 'stack.c'.
- Add any machine-specific assembler code in 'machine.c'.

G.3 Adding a new object file format

- Add a new FORMAT and/or DYNLINK definition in 'target.h'. The FORMAT macro specifies the object file format, or in some cases, the type of access library that is to be used to read the object file format. The DYNLINK macro specifies the type of dynamic linker that is used on a specific platform, and is used when obtaining information about the shared libraries that a program needs or has loaded.

- Make any necessary modifications to '`config.h`'.
- Add any support for stack traversal in '`stack.c`'.
- Add any support for symbol reading in '`symbol.c`'.

Appendix H Notes

This section contains information about known bugs and limitations in the mpatrol library as well as listing potential future enhancements.

Bugs should be reported to mpatrol@cbmamiga.demon.co.uk along with the details of the operating system, processor architecture and object file format that the mpatrol library is being used with — and don't forget to include the version of the mpatrol library you are using! Keep in mind that I only have access to a Pentium III Notebook PC running Red Hat Linux 6.2 and Windows 98, so I will be most likely unable to reproduce most of the system-specific bugs. A bug report that comes with an associated fix will be most welcome.

Enhancement requests and source code containing enhancements should also be sent to mpatrol@cbmamiga.demon.co.uk or the mpatrol discussion group at http://groups.yahoo.com/group/mpatrol/. If you are planning to implement an enhancement, let me know first in case I am (or someone else is) working towards the same goal — that way, work won't be wasted. If you wish to send me source code changes please send the changes as context diffs or in an e-mail attachment as a compressed tar archive.

H.1 Notes for all platforms

- Overriding the C++ operators to get source-level information using the preprocessor is still a bit dodgy and isn't likely to get much better, so `MP_NONEWDELETE` may have to be used a lot. Explicit references to `operator new` rather than `new` are likely to result in compilation errors, and the way that source level information is obtained for `operator delete` means that the resulting code will not be thread-safe. It might also be an idea to provide an allocation class from which user-defined memory allocators can be derived.
- Need to add support for other 64-bit processors in addition to the existing SPARC V9 support. This shouldn't be too hard, but I haven't got access to such processors to test them, so I haven't been able to yet. Also need to add support for building on targets and architectures where no operating system features are required or even available.
- Need to improve the concurrency in the thread-safe version of the mpatrol library. Currently, only one thread at a time is allowed to enter the mpatrol library, but it should be possible to extend this to protect individual data structures. Note that this will not only help to improve efficiency, but might also allow the mpatrol library to uncover bugs in thread-safe code that are timing-dependent.
- Need to make the library re-entrant. This could be achieved by moving the static variables in '`memory.c`', '`stack.c`', '`mutex.c`', '`diag.c`', '`trace.c`', '`option.c`' and '`sbrk.c`' into the `infohead` structure and then having an array of `infohead` structures from which to allocate new memory headers when a new one is required. This is only necessary for Amiga shared libraries and Netware NLMs since UNIX and Windows platforms allocate a new copy of the data section in a shared library or DLL when it is opened by a new process.
- Some implementations of call stack traversal are limited and will only likely work for unoptimised code. A much better solution would be write the implementations at a lower level in assembly, but this is much less portable. Perhaps there is a library which can be used to perform this across many operating systems and processor architectures, or maybe someone would like to write one[1]? I can think of many applications that would benefit from such a library besides this one[2].

---

[1] There is currently a library called StackTrace written by Bjorn Reese which invokes a debugger to generate a stack traceback on certain UNIX platforms. This method would be too slow for mpatrol to use though.

[2] Looking back at these statements about six months after they were written, it would appear that I have just written such a library judging by the number of architectures for which stack traversal is now supported.

- An alternative implementation for call stack traversal uses the functions `__builtin_frame_address()` and `__builtin_return_address()` that are available when the library is compiled with `gcc`. However, they can only traverse a number of stack frames at compile-time, not run-time so there is a maximum number of stack frames that can be traversed at any one time. The implementation depends on both of these builtin functions returning '`NULL`' when the top of stack is reached. If this is not the case then this method cannot be used or should only be used with a small number of fixed stack frames. However, perhaps there might even be a use for an option to limit the number of stack frames in stack tracebacks for systems that have no such limitation.
- Need to change `__mp_compareaddrs()` so that it will improve the detection of when to free memory allocations made by `alloca()` and its related functions. This will involve checking the common return addresses in the call stacks instead of just checking them if the stack depth is the same. Also, on systems that don't have full call stack traversal, the minimum number of bytes that stack frames should differ by should be platform-dependent since the current value is way too high.
- There is an issue with callback functions if they call mpatrol library functions, since this will lead to recursion. Callback functions could also be defined for `__malloc_hook()`, `__realloc_hook()` and `__free_hook()` in much the same way as for the GNU C library.
- Need to store filename and line number information in all call stacks so that the information can be used at program termination. May also need to display this information in the `__mp_printinfo()` function and add this information to the profiling output file so that `mprof` can make use of it. Stack traces also need to be displayed when the `__mp_checkrange()` and `__mp_checkstring()` internal functions fail. Likewise for the `strdup()` family of functions if the source string is invalid.
- In object file formats that support nested symbols (such as ELF), the current implementation will tend to show some shortcomings. This is because there is currently no nesting count in the function that deals with symbol name lookup, so the wrong symbol name may be displayed in diagnostics.
- In object file formats that don't store the sizes of symbols (such as basic '`a.out`', or when using the GNU BFD library), the current implementation will simply assume that the current symbol terminates at the beginning of the next symbol in the virtual address space.
- Add functions to start and stop profiling, and perhaps also to clear the profiling tables and begin a new profiling output file. Should also write more information to the profiling output file, such as the date that it was produced on and the word size of the processor that it was produced on, so that `mprof` will not crash when reading a profiling output file produced on a processor that has a different word size.
- Perhaps add the ability to profile memory operations such as `memcpy()` and `memset()` to the existing memory allocation profiling facility. Also, add options to `mprof` to write out files that can be used by chart drawing software for a better visualisation of the first few profiling tables.
- Extend the `mptrace` command to graphically display the size of the heap plotted against time and the allocation size frequency, and also display some useful statistics at the end. Also rewrite the GUI support to use GNOME instead of Motif, possibly also using GLADE.
- Add an option to `mptrace` to prevent the window being opened on systems where GUI support is enabled. Also add widgets to the `mptrace` window to pause and quit.
- Improve the speed of watch points by setting a range of allocation indices for which they will be used. This may require a lot of code changes in '`alloc.c`'.
- Add a software watch point facility that can be placed on ranges of addresses in the heap. Then, if a heap operation touches the watch point, either the user can be notified or a callback function can be called. The same could be done for local variables if the stack frame can be easily determined, which would also allow detecting if a read from or write to memory was performed just beyond the stack pointer.

- Add a CRC checksum to memory blocks and use it to check that freed memory allocations have not been corrupted when the 'NOFREE' and 'PRESERVE' options are in use on platforms which have no memory protection.
- Add an option to set up a timer that will automatically check the heap after a certain number of clock cycles have elapsed. This could be useful in programs that have long periods of time where no dynamic memory allocation functions are called, but heap allocations are still manipulated. In addition, checks could automatically be made upon receipt of special signals sent to the program by the user and information about the last successful verification of the heap could be used to narrow down problems.
- Add a diagnostic number count to each warning and error reported in the log file. This could then be used to implement a 'DIAGSTOP' option which would stop the program running after a certain number of diagnostics have been displayed.
- Perhaps add time information to the details stored about each memory allocation. This is probably not useful unless the system provides a high-resolution timer.
- Add an option (perhaps 'NOINTERNAL') to suppress the display of internal (recursive) memory allocations in the mpatrol log file and also prevent information about such allocations being written to the profiling output and tracing output files. This could also be extended to prevent memory leaks from being reported if the original allocations were made from a given set of functions.
- Maybe show the contents of the MPATROL_OPTIONS environment variable in the summary as well.
- Add versions of `mallopt()`, `mallinfo()`, `memorymap()`, `mallocctl()`, `mallocblksize()` and `msize()` which are provided in many other malloc libraries. These won't necessarily behave in exactly the same way as existing implementations, but at least there won't be link errors when compiling source code which uses them. Also, add support for setting as many remaining options in `__mp_setoption()` as possible and perhaps even some options before the mpatrol library has been initialised.
- Add similar functions to the GNU `mcheck()` and `mprobe()` functions.
- Perhaps add debugging/tracing versions of the string manipulation functions, such as `strlen()` and `strcmp()` in much the same way as was done for the memory operation functions. The only problem with this would be locale support, but perhaps it might be easier just to assume the C locale to begin with. Also need to have better detection of internal and free blocks when displaying memory range errors.
- Add wide-character equivalents of `memset()`, etc. These are defined as `wmemset()`, etc. and are now part of ANSI C. Also add `memdup()` and `xmemdup()`.
- Perhaps reimplement the standard I/O library for internal use by mpatrol, thus preventing recursive calls to `malloc()` each time a write to the log file occurs on some systems. Example code to do this was submitted by Alexander Barton (abarton@innotrac.com) and this may well be incorporated into the library at some point in the future.
- The 'LOG*' options could be extended to take a list of specific functions to log. They could also only log operations spanning a range of addresses or allocation indices as well.
- Add an option to limit the size of each memory allocation to a maximum number of bytes. This could be useful if a memory allocation function is called with an uninitialised variable.
- Add assertion macros to 'mpatrol.h' that can be used in program code. These could be used to assert that pointers have not been freed or are valid heap addresses, etc. They would be disabled if NDEBUG is defined.
- Add support functions that could be added to user code to enter and leave scopes in a source file and ensure that all allocations allocated within the scope are freed by the time the scope has been exited. A function could also be added to mark certain memory allocations as being validly in use so as to avoid leak warnings. Any attempts to free such allocations would result in an error. Other functions could be added to add or clear references to

certain memory allocations and to return the current number of memory allocations or bytes allocated.

- Add support for the '`-finstrument-functions`' option of the GNU compiler. This would allow mpatrol to keep track of the entry to and exit from every function, but would only work for code compiled with this option.
- Extend the Checker-support functions to store and check information about access permissions within heap memory and perhaps also in the stack as well, and also improve the diagnostics from the checker functions if they fail. Currently, the Checker-support functions only ensure that no memory accesses cross allocation boundaries or access free memory. Could also make use of the `etext`, `edata` and `end` pointers that are set at run-time on most UNIX systems. Need to properly implement `chkr_check_exec()`.
- Details of the segments which make up the executable file and any shared libraries could be made use of in order to detect operations which cross such segments. For example, a memory operation may erroneously cross the data and BSS segments. The symbol table for data symbols could also be used to provide much finer-grained error-checking. Need to make use of the `__mp_memquery()` function.
- Add an option to specify that all failed memory allocations should abort (or at least give a warning) instead of returning a '`NULL`' pointer. Also, perhaps add an option to display the partial contents of freed and unfreed allocations in the mpatrol log file.
- Perhaps add memory protection to the simulated `sbrk` heap.
- Add an option to report if one thread resizes or frees another thread's allocations. This may not be useful in most cases, but it might be possible to track down some obscure bugs in some situations.
- Perhaps add internationalisation support through the use of locales and message catalogs. Unfortunately, there does not appear to be a unified method for doing this across all platforms and there may also be issues with third-party libraries calling `malloc()` and other related routines when the mpatrol library is attempting to initialise itself.
- There is currently a problem when the mpatrol library encounters an illegal memory access on UNIX and Windows platforms, and there is a further illegal memory access when it is displaying the summary. This should be prevented by disabling the signal handler at its first entry.
- Need to make the mpalloc library threadsafe. This is only likely to be an issue when calling `MP_FAILURE()`. Should also add something similar to `xmalloc_set_program_name()` in order to show the program name when a memory allocation fails. If the C++ operators fail to allocate memory in libmpalloc then there should probably also be an exception thrown to mimic the behaviour of libmpatrol, although this isn't a big issue since the program should be completely recompiled to remove mpatrol debugging before a release. In the same vein, perhaps there should be some sort of support for `set_new_handler()` in libmpalloc.
- Add an option to write the mpatrol log file in HTML format, or even better XML format. Could also write the tracing output file in HATF format (Heap Allocation Trace Format) or the GNU `mtrace` format for processing by other utilities.
- The `mpsym` command could optionally preserve any stack traceback lines that already have symbolic or debugging information associated with them. It could also support more debuggers other than just `gdb`. Finally, it could support '`-`' as the filename for reading the mpatrol log file from the standard input file stream.
- Add a script to wrap around various popular C and C++ compiler drivers so that linking with the mpatrol library is much less laborious. In addition, a user-defined command or script file could be executed at the end of every invocation of the `mpatrol` command.
- Add a script to automatically run the mpatrol library tests. It could be quite hard to verify the tests since the heap addresses are likely to be different on every new build and will certainly be different across different platforms.

- Perhaps use GNU Autoconf to automatically work out values for '`config.h`' on the platform it is being built on, and also use Automake, libtool and install when building and installing files. Also update the `mupdate` shell script to automatically update the version numbers contained in the files in the '`pkg`' directory.
- The postscript version of the quick reference card seems to print at an unusual offset on some printers. In addition, the mpatrol manual should also be formatted in DocBook format once a suitable TEXinfo to DocBook translator is available.
- Perhaps add benchmark tests for dynamic memory allocation functions and memory operation functions. Obviously the mpatrol library would perform much worse than normal malloc libraries, but it would help to see just how much worse so that speed improvements could be made.
- Add support for the BeOS operating system, as well as MacOS, NeXT and OS/2. Perhaps MS-DOS might be possible as well.

H.2 Notes for UNIX platforms

- Need to improve watch point facility in order to speed it up by an order of magnitudes. This will most likely involve removing all watch points when entering the library and replacing them when returning to user code.
- Improve use of watch points by allowing an option which will only install write watch points instead of both read and write watch points. Not only will this speed up the use of watch points, but will also cause less problems with reading from misaligned memory allocations.
- There seems to be a problem on some UNIX systems in that the `mprotect()` call will not work unless it is used on memory that has been allocated with `mmap()`. This needs to be investigated further.
- There is currently a problem in that the call stack displayed from within the illegal memory access signal handler is not necessarily accurate with respect to the function at the top of the stack. In addition, signal handlers shouldn't technically call I/O functions in case of additional signals being caught so this may need to be improved.
- Need to add a way of initialising the thread-safe version of the library when it is not compiled on a system that supports '`.init`' sections, or if it is not compiled with the GNU C compiler, or if it is not compiled with a C++ compiler. Also perhaps need to support other threads packages instead of just POSIX threads.
- Need to add support for call stack traversal for the Alpha, and Itanium processor architectures. The current implementation of call stack traversal for the Motorola 88xx0 family is also a bit flaky and so should only be used when the library and program are built unoptimised. This could be improved on DG/UX platforms by making use of the TDESC information stored in the object files.
- Need to add support for obtaining the program name from the stack for the Alpha, Itanium and Motorola 88xx0 processor architectures. If there is no support for determining the filename that a program was invoked with then the '`PROGFILE`' option can be used to specify the program name at run-time.
- If the `MP_LIBRARYSTACK_SUPPORT` preprocessor macro is defined when building the mpatrol library on IRIX platforms then the '`libexc`' library must also be linked in. However, execution speed will fall dramatically since the `unwind()` function within that library calls `malloc()`, `free()` and other memory operation functions every time it is invoked. The only reason to use this library rather than the default method of stack traversal on MIPS would be if that method failed due to a bug (in which case it should be reported anyway).
- The mpatrol library `unwind()` function on MIPS platforms may have problems with call stack traversal in alternative stacks, such as those used by signal handlers. The call stack

will then terminate at the point at which the handler was called rather than unwinding to the top of the stack.

- The library cannot currently read any symbols from shared objects that have been read via `dlopen()`, `shl_load()` or similar functions. In addition, symbols cannot currently be read from any COFF or XCOFF shared libraries on LynxOS and some work needs to be done to build the mpatrol library as a shared library on LynxOS.
- Perhaps add support for reading HP/UX executable files and libraries in the SOM object file format without needing to use the GNU BFD library.
- Perhaps add support for other popular text editors in the `mpedit` command. Also add a way to specify editor options to the `mpedit` command.
- Add support for Digital UNIX, SCO UNIX, Ultrix and other non-System V UNIX operating systems. Also test on NetBSD, OpenBSD and SunOS as support has been written for these systems but is untested. The SunOS port requires an ANSI C compiler, though.
- The '`--dynamic`' option to the `mpatrol` command does not always work on systems whose dynamic linkers support the `LD_PRELOAD` or `_RLD_LIST` environment variables. This is because the object file format access libraries do not exist in shared form on such systems.
- Perhaps add files to build the mpatrol library and tools as a Debian package.

H.3 Notes for Amiga platforms

The Amiga has now been re-released as a completely new machine which comes with a completely new operating system. As a result, I will not be implementing any of the following features (or fixing any of the following problems) in mpatrol for the old AmigaOS. Support for the new AmigaOS may be added in the future.

- Perhaps add support for building mpatrol as an Amiga shared library. I attempted to do this in a previous release of mpatrol, but it would have involved too many source changes to get working fully. Perhaps it's not even worth implementing as the archive library works fine. However, if it is built as a shared library and `malloc()` and related functions are dynamically linked in some executable files then perhaps it would be possible to override these functions, thus getting the '`--dynamic`' option in the `mpatrol` command to work.
- Need to fix the problem where the maximum guaranteed alignment of an internal mpatrol library memory allocation is 8 bytes. However, this limitation does not affect the `memalign()` and related functions, and should not have any effect on the running of mpatrol since no datatypes require an alignment of more than 8 bytes.
- Need to add proper support for call stack traversal for both the Motorola 680x0 and PowerPC processor architectures. When `gcc` is being used then up to two stack frames can be traversed, but this should really be extended without requiring `MP_BUILTINSTACK_SUPPORT`. When SAS/C is being used then there is no support for call stack traversal.
- Need to add proper support for reading symbols from Amiga executable files. When `gcc` is being used then the BFD library routines will be called to determine the symbols from the executable file, but this will only work for objects compiled with `gcc` and there currently appears to be a problem getting the '`USEDEBUG`' option to work. When SAS/C is being used then there is no support for reading symbols from executable files. Also need to add support for reading symbols from any shared libraries that are required by the program.
- Possibly make use of other software such as Enforcer, Mungwall or MuLib in order to provide some form of memory protection. The features of SegTracker could also be put to good use so that the file and hunk location of entries on the call stack could be determined.
- Could add support for the '`EDIT`' and '`LIST`' options. This would probably involve finding a way to invoke a shell script without having to search for the script file or allocating memory in the process.

- Add GUI support for the `mptrace` command.
- When using SAS/C it is currently not possible to override the definition of `malloc()`, etc., without including the '`mpatrol.h`' header file first. This is because the compiler startup code and libraries call `malloc()` before everything is set up, and so the library cannot properly initialise itself if the `malloc()` that the startup code finds is the `malloc()` in the mpatrol library. This restriction does not exist when using `gcc`.
- Add support for the Amiga in the threads test in '`tests/pass/test5.c`'. The Amiga doesn't really have support for threads but its processes are similar enough to threads.
- Perhaps add an `Installer` installation script with icons.

H.4 Notes for Windows platforms

- Need to add support for processors other than the Intel 80x86. However, about 99% of Windows platforms run on this processor family — does anyone really use Windows with other processors? Also finish Cygwin support, although this is effectively mpatrol built with '`-DTARGET=TARGET_UNIX`' support on Windows platforms.
- Perhaps add support for compiling the mpatrol library with `gcc` on Windows platforms so that the GNU BFD library can be used as well.
- There seems to be a problem when mixing the archive version of the mpatrol library and the Microsoft C run-time library DLL, and vice versa. This needs to be looked into, but for the moment, don't mix them.
- The library cannot currently read any symbols from DLLs that have been read via `LoadLibrary()`.
- Perhaps add support for the `mpatrol` command's '`--dynamic`' option by preloading the mpatrol DLL from the `mpatrol` command.
- Could add support for the '`EDIT`' and '`LIST`' options. This would probably involve finding a way to invoke a batch file without having to search for the batch file or allocating memory in the process.
- Add GUI support for the `mptrace` command.
- Add a Windows resource file to the mpatrol library with copyright and version information.
- Perhaps add an `InstallShield` installation script with icons.

H.5 Notes for Netware platforms

There doesn't appear to have been any interest in the Netware version of mpatrol and as a result I will not be implementing any of the following features (or fixing any of the following problems) in mpatrol for Netware. I don't even have access to a Netware machine so someone else would have had to have done it anyway.

- The library has not yet been built (let alone tested) on Netware platforms. The names of the system functions that the library calls for Netware were obtained by looking at Novell's developer documentation, so they may not even compile correctly without modification.
- Need to add support for building the mpatrol library as an NLM. This is not currently a high priority requirement as the archive library should suffice for most purposes. However, if it is built as an NLM and `malloc()` and related functions are dynamically linked in some executable files then perhaps it would be possible to override these functions, thus getting the '`--dynamic`' option in the `mpatrol` command to work.
- Need to add support for processors other than the Intel 80x86. However, about 99% of Netware platforms run on this processor family — does anyone really use Netware with other processors?

- Need to add way to determine when the base of the stack has been reached during call stack traversal, since on Netware every application is really a thread running under one large process.
- Need to add support for reading symbols from Netware load modules. Also need to add support for reading symbols from any NLMs that are required by the program. This may be possible in a limited fashion by using the GNU BFD library, but may only work with code compiled with `gcc`.
- Could add support for the '`EDIT`' and '`LIST`' options. This would probably involve finding a way to invoke a batch file without having to search for the batch file or allocating memory in the process.
- Add GUI support for the `mptrace` command.
- Need to investigate if it is safe (or even possible) to override the definitions of `malloc()`, etc., without including the '`mpatrol.h`' header file first. Currently, non-macro definitions for these functions have been disabled in the Netware version of the library in case they affect other NLMs that are currently running.

Appendix I Frequently asked questions

This section contains frequently asked questions about the mpatrol library and their corresponding answers or solutions.

I.1 Documentation

1. I can't seem to format the TEXinfo manual for mpatrol into anything that I can view or print. What am I doing wrong?

   You'll need to have the appropriate document formatting programs installed on your system before you can do this, and even then you'll also need to have suitable software for viewing or printing the formatted documents. The mpatrol distribution should already contain the latest mpatrol manual in a variety of formats and should also contain a file telling you where to get programs that can be used to view or print these files. Alternatively, you can browse the latest mpatrol manual on-line at `http://www.cbmamiga.demon.co.uk/mpatrol/`.
2. I'd like to convert the mpatrol manual to a different documentation format but there is no support for that format in the '`Makefile`'. How would I go about doing this?

   Since TEXinfo is intended to be converted to other documentation formats it should be fairly easy for you to find a tool which will convert it into your desired format. I plan to also provide the mpatrol manual in DocBook format if and when a suitable TEXinfo to DocBook converter becomes available, but I won't provide preformatted versions of the mpatrol manual in any other format which isn't already supported.
3. Why is the reference card not centred in the middle of the page when I print it?

   The reference card has three columns in landscape format and as a result requires smaller margins than LaTEX normally uses. When `dvips` converts the DVI file to a postscript file it refers to a configuration file set up for a specific printer so that it knows what that printer's capabilities are. However, you can instruct `dvips` to offset the page by a given amount with the '`-O`' option so that it appears centred when printed. I find that '`-O -0.75in,0.25in`' works for me. Note that the default paper size for the reference card is DIN A4, but you can change it to US letter in the LaTEX source file.
4. How do I install the mpatrol manual as a GNU info file?

   Assuming you have the GNU info file built and copied to your system's info file directory, you should use the `install-info` command to place an entry for mpatrol in your system's GNU info directory file, otherwise the GNU info reader may not be able to locate the mpatrol entry. You may also need to modify your `INFOPATH` environment variable if you installed the GNU info file in a non-standard place.
5. How do I install the mpatrol manual pages?

   This is very system-dependent, but need only be done on UNIX systems since they cannot be used on other platforms. The unformatted manual pages exist in '`man/man1`' and '`man/man3`' and should be copied to your system's manual page directory. If you don't have the `nroff`, `troff` or `groff` commands installed on your system then you may also need to copy the formatted manual pages, located in '`man/cat1`' and '`man/cat3`'. You may also need to modify your `MANPATH` environment variable if you installed the manual pages in a non-standard place, and some systems require you to update the *whatis* database after installing new manual pages, by running `makewhatis`, `catman` or equivalent.

   Alternatively, the mpatrol manual pages can be built in a variety of different documentation formats that can be viewed or printed without the need for a `man` command. If you have the correct tools installed on your system then you should be able to do this by examining the '`Makefile`' in the '`man`' directory. The mpatrol distribution should already contain the latest mpatrol manual pages in a variety of formats and should also contain a file telling you where to get programs that can be used to view or print these files.

6. Why does the 'libmpatrol.3' manual page not display correctly when I view it with the man command?

   This is likely to be due to the tbl command not being run to process the tables when the man command displays the manual page. Many UNIX systems look at the first line of the manual page to see what filters to run the page through before it is displayed, but some systems do not recognise this and instead rely on an environment variable such as MANROFFSEQ to specify which filters are to be run. Look at the manual page for the man command on your system to find out more information.

I.2 Building

1. Why does the 'Makefile' assume that I am building mpatrol on platform X when I am really building on platform Y?

   The 'src/config.h' and 'src/target.h' header files attempt to obtain as much information from the compiler as possible, mainly from any predefined preprocessor macros that it defines during compilation. If this information is incorrect then you can override the TARGET, SYSTEM, ARCH, ENVIRON, FORMAT and DYNLINK preprocessor macros defined in 'src/target.h' to suit your particular system by explicitly defining them in CFLAGS within the 'Makefile' when you build mpatrol. You could also choose to build different versions of mpatrol with different settings of ENVIRON, FORMAT or DYNLINK on a single system if you wish to by changing ENVIRON, FORMAT or DYNLINK for different builds.

2. The processor family I am compiling on supports both 32-bit and 64-bit modes of operation. How do I specify which I want?

   You will have to look at the documentation for the compiler you are using in order to find out how to specify which operating environment you wish to target. For example, if you are using the Sun C compiler on a SPARC V9 Solaris machine then you should specify the '-xarch=v9' option in the 'Makefile' when you are building mpatrol in order to target the 64-bit environment. If you think that you are already using the correct option, but the mpatrol code is still being built to support the wrong environment then you could try explicitly setting the ENVIRON preprocessor macro in the 'Makefile'.

3. I cannot include 'mpatrol.h' from my C++ source code as I get lots of compilation errors. Why is this and what can I do to prevent them?

   The most likely reason that you are getting errors is because you are calling placement new, and the way that mpatrol derives source information from calls to operator new is by defining a macro called new, thus causing lots of problems when calling placement new or explicitly calling operator new. You can either try not to use placement new or you can define the preprocessor macro MP_NOCPLUSPLUS when compiling your source file, which will disable the overriding of any C++ operators in 'mpatrol.h'. Alternatively, if you define MP_NONEWDELETE then you can use MP_NEW, MP_NEW_NOTHROW and MP_DELETE in order to call the mpatrol versions of the C++ operators.

4. I still have the above problem, but I don't think it's due to placement new since the compiler complains about operator new[], so could that be a clue?

   Yes. The most likely reason is that the C++ compiler does not support the array new and delete operators. These were introduced some time before the standardisation of the C++ language but some compilers may not yet have support for them. It may be that you have to use a special compiler option to enable support for these operators, but if not you will probably have to edit 'mpatrol.h' to temporarily allow your files to compile.

5. I tried both of the above suggestions, but I still can't get my C++ source code to compile. I'm using an old C++ compiler so could that be a problem?

   Yes. The 'mpatrol.h' header file defines new versions of the C++ dynamic memory allocation operators using exceptions and namespaces as required by the ANSI C++ standard. If your C++ compiler has no support for these then you should compile your C++ source files with MP_NOCPLUSPLUS defined.

6. I'm calling `operator new` (not the *nothrow* version) from my C++ source code but when my program runs out of memory the '`OUTMEM`' error is given in the mpatrol log file rather than throwing a `std::bad_alloc` exception. Why is this?

   Sounds like the mpatrol library was built with a C compiler. In order for the mpatrol versions of `operator new` and `operator new[]` to throw an exception when they run out of memory, the mpatrol library must have been built with a C++ compiler. The '`OUTMEM`' error is only given when there is no way to throw an exception.

7. Why am I unable to call the mpatrol version of `alloca()`? I only ever seem to call the default version.

   Most implementations of the `alloca()` function are compiler builtins which will be converted to inline assembler or object code in order for them to be able to dynamically modify the calling function's stack frame at run-time. As a result, the call to `alloca()` is recognised as an intrinsic keyword and is dealt with specially by the compiler. However, if this can be intercepted by the preprocessor before the compiler parses the source code then the call can be redirected to another function. This is one of the functions of the '`mpatrol.h`' header file, which means that it must be included before the first call the `alloca()`. If `alloca.h` is also being included then `mpatrol.h` must be included after it, otherwise it may redefine `alloca()` back to the default version.

8. Why do some of the '`Makefile`'s contain the '`-fno-inline-functions`' option as part of `OFLAGS`?

   The '`-fno-inline-functions`' option is a `gcc`-specific option which instructs the compiler not to inline any functions. This is necessary on some platforms where function call stack traversal is supported, since function inlining may significantly alter the layout of a program's stack. Normally this option is only required when building the mpatrol library, but on some platforms function call stack traversal may not work properly unless this option (or equivalent) is used for all compiled code.

9. What does the `MP_ALIGN` definition in '`mpatrol.h`' do?

   It is a preprocessor macro function that is used to return the minimum alignment in bytes required for a specified type at compile-time. It is used in the `MP_MALLOC` family of functions to specify the required alignment of the memory allocation that is to be used to store the specified type. Some compilers provide a feature that can be used to determine the minimum alignment of a type at compile-time. For all others, this macro evaluates to '`0`'.

10. What does the `MP_INLINE` definition in '`mpatrol.h`' do?

    It is used in the definition of the debugging versions of the C++ operators in '`mpatrol.h`' so that they are inlined correctly. We want to define the C++ operators so that they will be inlined in every source file that uses them and also not clash with the versions defined in the mpatrol library or the standard C++ library. Traditionally, this is done by defining them to be `static inline`, which means that any non-inlined definition will be local to each object file. An even better technique is available with the new C++ standard which allows `extern inline` definitions, meaning that no definition will be available if the function is not inlined. Unfortunately, if optimisation is turned off in the compiler then no inlining will usually be performed and so the definitions will be real functions. Luckily, on ELF platforms the `extern inline` function definition will have a weak visibility and so will not clash with library functions.

11. Why do I get different stack traces in the mpatrol log file from the C++ operators in '`mpatrol.h`' when optimisation is turned on and off in the compiler?

    When the compiler is optimising it will invariably be performing inlining, in which case each inlined function will share the stack frame of its caller when it is called — the mpatrol library cannot detect this. In order to cope in both situations, the non-inlined case will contain the name of the C++ operator at the top of its stack, even though it will be removed in the inlined case.

12. How do I build the mptrace command with GUI support?

    The GUI support for the mptrace command is currently written to use Motif and X Windows and so can only be built on systems with these libraries and run on systems with an X server. This will most likely be possible only on UNIX platforms. LessTif can be used instead of Motif if that is all that is available on your system.

I.3 Linking

1. Why do I get undefined symbols when linking with the mpatrol library?

   This is most likely caused by the mpatrol library requiring additional symbols defined in an object file access library. If mpatrol was built with FORMAT=FORMAT_COFF or FORMAT=FORMAT_XCOFF then you'll need to add '-lld' (or equivalent) to the compiler command line straight after '-lmpatrol'. If mpatrol was built with FORMAT=FORMAT_ELF32 or FORMAT=FORMAT_ELF64 then you'll need to add '-lelf' (or equivalent) to the compiler command line straight after '-lmpatrol'. If mpatrol was built with FORMAT=FORMAT_BFD then you'll need to add '-lbfd -liberty' (or equivalent) instead. If you are using the thread-safe version of mpatrol then you may also need to link with the system threads library.

2. Why do I still get undefined symbols on HP/UX, IRIX or Windows platforms, despite following the above instructions?

   If the symbol is called U_get_previous_frame on HP/UX then you still need to link with the system stack traceback library, 'libcl.sl'. If the symbols are called exc_setjmp and unwind on IRIX and you defined the MP_LIBRARYSTACK_SUPPORT preprocessor macro when building the mpatrol library then you still need to link with the system exception library, 'libexc.so'. If the symbols all begin with Sym on Windows platforms then you still need to link with the system symbol access library, 'imagehlp.lib'.

3. I tried all of the above, but why is the SymGetLineFromAddr symbol still undefined on Windows platforms?

   This is due to the 'imagehlp.lib' or 'imagehlp.dll' libraries on your system being out of date. The SymGetLineFromAddr() function was added to this library at a much later date from the original release so if you want the USEDEBUG option to work you should try to get an updated library from Microsoft. Alternatively, you can disable the call to it in __mp_findsource() but the 'USEDEBUG' option will no longer work.

4. Why do I get duplicate definitions of symbols when linking with the mpatrol library?

   This is most likely caused by your code, or a library, providing definitions of malloc() and free() which conflict with those defined in the mpatrol library. You'll need to disable these in order to perform a successful link and use the replacements in mpatrol instead.

5. I linked my program to a shared library version of mpatrol. Now, when I try to run my program, the system complains that it cannot find the mpatrol library. How do I get this to work?

   You need to tell the system where to find the shared library version of the mpatrol library, either by setting your LD_LIBRARY_PATH environment variable (or just PATH on Windows platforms), or by embedding the full path to the library into the executable when you link your program by setting the LD_RUN_PATH environment variable.

6. I linked my program to a shared library version of mpatrol. Will future releases of mpatrol remain compatible with this version or will I have to relink my program?

   Backwards compatibility is not generally guaranteed, but should be preserved if only the bug fix part of the mpatrol version number has changed, with the major and minor versions staying the same. For example, versions 1.0.3 and 1.0.8 should be compatible, but upgrading to version 1.1.0 may require a relink.

7. I have linked my program with the DLL version of the mpatrol library on Windows but it crashes when I run it. I suspect that the crash is occurring when the mpatrol library is being initialised, so what is going wrong?

   There appears to be a problem when using the mpatrol DLL and the static version of the Microsoft C run-time library, and also a problem when using the static version of mpatrol and the Microsoft C run-time library DLL. Luckily, if you ensure that you use either both static libraries or both DLLs at the same time then the problem should go away. There doesn't seem to be an easier way around it at this time or, for that matter, an explanation for why it happens.
8. Why are mpatrol library functions not called from shared libraries on AIX?

   AIX uses static shared libraries instead of dynamic shared libraries, which means that all shared library bindings are resolved at link time rather than load time (i.e. you must specify which shared libraries resolve all of the undefined symbols that result when building a shared library). If you would like mpatrol library functions to be called from a shared library, you must rebuild the shared library with '`-lmpatrol`' on the link line. However, this means that you cannot override `malloc()`, etc., in shared libraries that you cannot rebuild unless you link statically with the archive library versions instead.

I.4 Running

1. I've just linked and run my program with the mpatrol library, but the resulting log file doesn't contain any useful information. Why does it not contain a list of all memory transactions or show any unfreed memory allocations?

   By default, the mpatrol library will only write a summary of library settings and statistics to the log file, and that will only occur on successful program termination (i.e. when `exit()` is called). If this does not appear then it is likely that your program (or some other library function) called `abort()` due to a fatal error. However, there are a multitude of different options that you can pass to the mpatrol library via the `MPATROL_OPTIONS` environment variable that will allow you to control what is logged and what is not. Note that the `mpatrol` command will always log all calls to allocate, reallocate and free memory by default.
2. Why does my C++ program crash at program termination when it is linked with the mpatrol library and it appears to be doing nothing wrong?

   If your program contains file-scope objects whose constructors get called before `main()` and whose destructors get called after `main()` then it is likely that one of these destructors is allocating memory after the mpatrol library has terminated. This should already be resolved if you built the mpatrol library on a platform that supports '`.init`' and '`.fini`' sections or if you built it with the GNU compiler or a C++ compiler. However, in certain circumstances this may not work so you may wish to try terminating the mpatrol library by getting it to register itself with `atexit()` instead, which will hopefully resolve the problem. You can do this by rebuilding the mpatrol library with the `MP_USE_ATEXIT` preprocessor macro defined.
3. I linked my program with the mpatrol library to trace all of its memory operations, such as `memcpy()` and `memcmp()`, but I get nothing in the log file. Why is this?

   On systems that do not support '`.init`' and '`.fini`' sections or are not `gcc` or C++ based then the memory operation functions will not automatically initialise the mpatrol library since on many systems the startup routines call them very early on. On such systems, if your program does not call any memory allocation functions to initialise the mpatrol library then you must explicitly call the `__mp_init()` function. All memory operation functions following that call with then be traced.
4. Why does the '`USEDEBUG`' option not work for me?

   Firstly, you have to ensure that you have built the mpatrol library with support for the GNU BFD object file access library by compiling with the `FORMAT=FORMAT_BFD` preprocessor macro definition, or you are running on a Windows platform. Secondly, you have to ensure that you have compiled all relevant object files with debugging information enabled (usually by adding an option to the compiler command line), although the mpatrol library does not need to be compiled this way. The file and line number information will hopefully then appear in the log file for all symbols that have associated debugging information. If none of the above suggestions work, you may still be able to get this information with the `mpsym` command.

5. Why does the `mpatrol` command ignore the current value of the `MPATROL_OPTIONS` environment variable?

   Because I would most likely get lots of bug reports or queries from people who had forgotten that they had set some options in the environment variable and had then not seen the expected behaviour from the options they specified to the `mpatrol` command.

6. Why does the mpatrol library not read the symbols in my executable file on Windows platforms?

   If the mpatrol library was compiled with the `FORMAT=FORMAT_PE` preprocessor macro defined then you must ensure that you compile your files with debugging information enabled (using the '`-Z7`' or '`-Zi`' options in Visual C++) and that you tell the linker that you wish to preserve the debugging information in the executable file (using the '`-debug`' and '`-pdb:none`' options in the Microsoft linker). Unfortunately, if you do not do this then the final executable file will not have a symbol table and so the mpatrol library cannot give symbolic stack tracebacks.

7. Why do some mpatrol log file entries only contain a partial call stack rather than following the function call stack back to the call to `main()`?

   This could be because the mpatrol library was compiled with limited call stack traversal support via the `MP_BUILTINSTACK_SUPPORT` configuration macro. However, it could also mean that the mpatrol library encountered a corrupt frame pointer when traversing the call stack and had to terminate the recursion. The frame pointer *must* be preserved from function to function on most platforms, otherwise the stack cannot be traversed. See your compiler manual for further details.

8. I am trying to use the `mpatrol` command to debug an executable file that was not originally compiled with the mpatrol library. However, even though it runs successfully, no mpatrol log file is produced. Why is this?

   First, check that you are passing the '`--dynamic`' option to the `mpatrol` command and, if necessary, the '`--threads`' option as well. If that doesn't work then check that the executable file has been dynamically linked; statically linked executables cannot be forced to use the mpatrol library. If it still doesn't work then it may be that the dynamic linker on your system doesn't have the ability to preload any shared libraries that have been specified in a special environment variable, in which case you can't use this feature.

9. I am attempting to run a multithreaded C++ program with the mpatrol library on Linux. However, my program crashes before `main()` and the debugger shows that the failure is in `__sigaction()` which is called from `__mp_initsignals()`. Is the fault with the mpatrol library?

   There have been many reports of this problem and it turns out to be an issue with shared library dependencies. ELF shared libraries may contain initialisation functions that are executed before `main()`. However, sometimes the order in which these functions are executed is critical. In this case it is likely that the mpatrol and pthreads libraries are being initialised in the wrong order. You must ensure that '`-lpthread`' appears near the very end of the link line after all user libraries, and you must also ensure that none of the user libraries have a dependency on '`libpthread.so`'. You can verify this by running the `ldd` command on them.

10. I know that there's a definite heap corruption problem in my program as it keeps crashing in unrelated code due to pointer corruption, and when I link with the mpatrol library it stops crashing. What can I do?

Try as many of the relevant mpatrol run-time options as possible and make sure that you closely examine the mpatrol log file for warnings and errors — your problem may have been noticed by the mpatrol library but it may not have considered it a fatal error and continued execution. If this still doesn't show up anything then you can probably rest assured that you have a memory corruption problem but you may need to use a commercial product such as Purify to isolate it. If that fails then you'll just have to employ the traditional debugging method of single-stepping through your program in a debugger until something unusual or unexpected happens.

11. If I link my program to version 1.0 of the mpatrol library then I cannot interrupt it using the keyboard, which I would normally be able to do without using mpatrol. Is this a bug?

    Not really, but it is undesirable behaviour in most cases, which is why it was removed in later releases of mpatrol and replaced with the '`SAFESIGNALS`' option. The reason that the program could not be interrupted using the keyboard was that mpatrol would ignore such signals when its library code was being executed, otherwise user-defined signal handlers that used `malloc()` and related functions would have the capability to cause lots of undesirable side effects. However, this does not normally happen, which is why the behaviour was moved to an option for those that needed it.

12. Why does mpatrol not report an illegal memory access when it can be detected by a debugger?

    First of all, illegal memory accesses can only be detected on systems that support virtual memory, so that precludes AmigaOS and Netware. Secondly, it might be possible that something is overriding the illegal memory access handler that mpatrol sets up when it is first initialised. If your program, or an external library, sets up a signal handler that handles `SIGBUS` or `SIGSEGV` (or their equivalent on Windows platforms) then mpatrol will no longer be able to catch illegal memory accesses. You can either try to live with that, or you could try disabling the overriding handlers.

13. How do I set a breakpoint on the `malloc()` function when it is implemented as a preprocessor macro in '`mpatrol.h`'?

    There are four different mpatrol interface functions which are used to allocate memory, duplicate strings, reallocate memory and deallocate memory. If you look in '`mpatrol.h`' you should be able to see the name of the function that will be called when the macro is invoked. The same goes for the memory operation functions.

14. I've linked and run my program with mpatrol under UNIX and it uses a large amount of heap memory. However, it crashes near the end of execution and then proceeds to freeze up the whole system, sometimes requiring a reboot. What am I doing wrong?

    The most common possible explanation for this is that you are running your program with too much access to system resources. What is likely to be happening is that when your program crashes the system attempts to dump the entire process image to a core file for later debugging in a non-symbolic debugger. If the process has a huge heap then the core file is also going to be huge, thus resulting in a massive file that may lead to the system thrashing while it attempts to write it to the disk. Technically, the system has not frozen, but it is likely to take a long time to finish writing the file. The best solution involves setting your program's maximum core file size to a reasonable limit (or just zero), and also possibly limiting your program's maximum data segment size as well. These can be set from the shell but the exact details on how to do this differ between shells.

15. Why does my program run so slowly after I link it with the mpatrol library?

    Normal malloc libraries are optimised for speed but will typically fall over at the slightest hint of an error. Debugging malloc libraries are written to provide as much debugging information as possible whilst performing a multitude of additional checks, which is why they may run much slower. However, you can control which checks are performed (and when) by using the `MPATROL_OPTIONS` environment variable. Performance may also be lost if you make lots of small memory allocations rather than fewer larger allocations, but that is mainly due to the overhead of storing the extra tracing details for each memory allocation.

16. My program is written in C++ and is linked to the mpatrol library, but how do I go about demangling the C++ symbol names that are shown in the stack tracebacks in the resulting log file?

    Because there is no standard way of mangling C++ symbol names, various compilers and operating systems have taken different approaches to C++ name mangling, many of which differ significantly from the method suggested in *The Annotated C++ Reference Manual* by Margaret Ellis and Bjarne Stroustrup. However, most compilers come with a demangling tool which can be used in a command pipe to accept mangled names on its standard input file stream and demangle them on its standard output file stream, and so can be used to process the mpatrol log file. Note that mpatrol automatically demangles C++ symbol names on Windows platforms as Microsoft's name mangling is quite unreadable and would be hard to demangle using a command line tool.

17. Why does my program not stop when the mpatrol library notices an error?

    The library was written to give as much information as possible and so sometimes, when a non-fatal error is discovered, the library will write the error message to the log file and continue in the hope of being able to uncover more errors during the execution of the program. This means that you should always check the number of warnings and errors given in the summary at the end of program execution, and then search backwards in the log file for '`WARNING`' or '`ERROR`'.

18. I have linked my program with the mpatrol library on an Amiga or Netware machine, but when it runs it still crashes the entire system. Why is this?

    AmigaOS and Netware do not have virtual memory and so do not have memory protection turned on by default. This means that any rogue write to an erroneous address may actually overwrite the data of another process or perhaps even the operating system, thus bringing the entire machine down. There are several third-party system utilities available for the Amiga to add memory protection to machines with built-in MMUs, which can then be used in conjunction with mpatrol. I'm not sure about the availability of such software for Netware.

19. I have built the mpatrol library with `gcc` on AmigaOS and have successfully linked it to my program. However, why are none of the options in the `MPATROL_OPTIONS` environment variable recognised when I run it?

    The `getenv()` function in the GNU C library is not compatible with the AmigaDOS `SetEnv` and `GetEnv` commands since it does not treat environment variables as files located in '`ENV:`' and is only compatible with software that uses the ixemul library. However, the `env` command that comes with most GNU software distributions allows you to set an environment variable that the GNU `getenv()` function can read when you are running in AmigaDOS.

20. How do I suppress all diagnostic output from the mpatrol library?

    You can do this by setting the mpatrol log file to be your system's *bit bucket*, which is '`/dev/null`' on UNIX platforms and '`NIL:`' on AmigaOS. There doesn't appear to be an equivalent way to do this on Windows or Netware.

I.5 Files

1. Why is there a '`libmpatrol.o`' target in the UNIX and Amiga '`Makefile`'s?

   This is simply used to build the mpatrol library as one large object file for full incorporation into other libraries and was used during the development of mpatrol. On UNIX platforms some linkers support the '`-r`' option for combining many object files into one large object file, but this is not universally supported, hence the reason for using the compiler instead. Because all of the source files are compiled at once, there may be conflicts with system header files when `malloc()` and its related functions are being compiled, which is why such an object file is not built by default. In addition, platforms which require the assembler routines in '`machine.c`' cannot build the mpatrol library as one large object file from '`library.c`'. Note that the Windows and Netware '`Makefile`'s use '`libmpatrol.obj`'.

2. What are the '`CVS`' subdirectories that come with the mpatrol distribution?

   CVS stands for Concurrent Versions System and is a project version control system. All of the source files that comprise an mpatrol release are stored in a central CVS repository so that previous releases can be easily retrieved, but the CVS system needs to have a way of determining the versions of currently checked-out files, hence the '`CVS`' subdirectories. You shouldn't need to worry about them, so just ignore them, and in later releases they should have been removed before a distribution was made.

3. Why does the `mpsym` command not work for me?

   Firstly, you have to ensure that you have compiled all relevant object files with debugging information enabled (usually by adding an option to the compiler command line). The file and line number information will hopefully then appear in the log file for all symbols that have associated debugging information when you run the `mpsym` command on the log file. Alternatively, it could be that your system does not have `gdb` or any of the required UNIX text processing tools installed, in which case you might want to try installing them.

4. How can I customise the `mpedit` command if I do not have the appropriate permissions to edit the file that was installed on my system?

   You just need to take a copy of the installed `mpedit` command and place it somewhere that will be picked up earlier on your command search path. You can then edit your copy of the file and add support for your favourite text editor.

5. What does the `mupdate` shell script do?

   This is for my use in order to automate every new release of mpatrol. You should never need to run this script and it should not be installed anywhere on your system. This script also uses and modifies the '`VERSION`' file and updates the '`NEWS`' and '`ChangeLog`' files.

Appendix J Related software

The mpatrol library was designed to solve most common heap-related problems, but there may be some cases where a different approach is needed, or a commercial package is required. I have attempted to provide an overview of the different types of malloc libraries and memory debuggers available below, along with a comprehensive list of related software.

The most basic type of heap debugging system simply requires the redefinition of `malloc()`, `realloc()` and `free()` (and related functions) with debugging versions that record the file and line number at which allocations occur. This might require modifications to the source code in order to call these new functions or it can be done through preprocessor macros which will require all source files using the memory allocation functions to be recompiled. Such a system will most likely live on top of the existing system malloc library, but will provide an additional layer with which to store more information for debugging purposes. MEM by Walter Bright is a good example of this type of library.

On many operating systems it is usually possible to write replacements for the normal memory allocation routines and place them in a library so that they can be linked in to override the system malloc library without requiring recompilation of any source files. Such malloc libraries must take control of the heap directly and so usually contain more features, including being able to track memory leaks and place fence posts around allocations. Dbmalloc by Conor P. Cahill and Dmalloc by Gray Watson are two of the most popular of these types of libraries since they are available on a wide range of platforms. Electric Fence by Bruce Perens also makes use of the memory protection facilities found in UNIX systems in order to force programs that access free or freed memory or read or write beyond the bounds of a memory allocation to crash at the point that the illegal memory access is made, rather than crashing at the next memory allocation.

For debugging all memory access errors (not just those on the heap) it is necessary to modify (instrument) the machine code that is to be run so that each individual load from memory and store to memory will be checked. One method of doing this is to modify the code produced by a compiler (such as is done by Checker written by Tristan Gingold) but this has the disadvantage of only working within the object files that have been produced by that compiler. It is also possible to modify the source code itself using source to source translation (such as is done by Parasoft Insure++) or instrument all accesses to memory in assembler source files (as performed by APurify written by Samuel Devulder). However, both of these methods suffer from the same drawback as compiler-generated instrumentation. Yet another alternative is to wait until link-time and then instrument the individual object files and libraries before they are linked into an executable file. This is effectively what Purify from Rational Software does, although Memory Advisor from PLATINUM Technology does roughly the same except that it disassembles the object files into a platform-independent format before instrumenting them.

Rather than modifying a program in order to add debugging code, it is sometimes possible to use a dedicated memory debugger in order to quickly catch any problems. ZeroFault from The Kernel Group debugs all memory-related operations in a program while it is running, whilst AProbe from OC Systems allows users to dynamically add probe modules at run-time in order to locate errors or perform profiling. If such a memory debugger is not available for your system, you may still be able to dynamically link a malloc library into your application at run-time if the operating system supports it. NJAMD by Mike Perry makes extensive use of this feature on some UNIX systems. On operating systems that do not support virtual memory but have hardware memory protection, it is sometimes possible to trap memory errors before they bring down the whole system. On the Amiga, Enforcer by Michael Sinz runs in the background and detects many common memory access errors in running applications, whilst on the Macintosh, QC by Onyx Technology provides roughly the same functionality.

A list of over eighty different items of software which help in debugging dynamic memory allocation problems is given below[1]. They all provide some of the features that mpatrol contains and you may wish to use one of them to solve your problem if you have trouble using mpatrol. I have only ever used Dbmalloc, Dmalloc, Electric Fence and Mprof, so I can't vouch for any of the others, although if you have any recommendations feel free to let me know so I can add them to this list. In particular, there seems to be a shortage of such programs for Netware platforms.

- AProbe

  Author OC Systems (info@ocsystems.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.aprobe.com/

  Overview Instruments a program using Dynamic Action Linking in order to track down memory corruption and monitor memory usage, among other things.

- APurify

  Author Samuel Devulder (Samuel.Devulder@info.unicaen.fr)

  License Free Software

  Platforms AmigaOS

  Location http://wuarchive.wustl.edu/~aminet/dirs/dev_debug.html

  Overview Instruments an assembler source file to insert code that checks all memory accesses.

- BoundsChecker

  Author NuMega Corporation (info@numega.com)

  License Commercial Software

  Platforms Windows, MS-DOS

  Location http://www.numega.com/

  Overview Detects and diagnoses errors in static, stack and heap memory and in memory and resource leaks.

- C++ Debugging Support Library (libcwd)

  Author Carlo Wood carlo@alinoe.com

  License Q Public License

  Platforms Various UNIX

  Location http://sourceforge.net/projects/libcw/

  Overview A C++ debugging library that can also detect memory corruption and memory leaks.

- Ccmalloc

  Author Armin Biere (biere@inf.ethz.ch)

[1] This list can be considered to be a slightly more up to date version of *Debugging Tools for Dynamic Storage Allocation and Memory Management* (http://www.cs.colorado.edu/~zorn/MallocDebug.html) by Ben Zorn (zorn@microsoft.com).

License GNU General Public License

Platforms Various UNIX

Location http://www.inf.ethz.ch/personal/biere/projects/ccmalloc/

Overview Can interface with `gdb` to find memory leaks, multiple deallocations and memory corruptions in C or C++ programs.

- Chaperon

  Author John Reiser (jreiser@BitWagon.com)

  License Commercial Software

  Platforms Linux

  Location http://www.bitwagon.com/chaperon.html

  Overview Runs existing Intel Linux binary application programs, but checks for and reports bad behaviour in accessing memory.

- Checker

  Author Tristan Gingold (bug-checker@gnu.org)

  License GNU General Public License

  Platforms Various UNIX

  Location http://www.gnu.org/software/checker/checker.html

  Overview Detects illegal memory accesses when reading from uninitialised memory, writing to freed memory or outside memory blocks. Also contains a garbage collector for detecting memory leaks.

- CMEM

  Author Brett Hunsaker (hunsaker@eisner.decus.org)

  License Free Software

  Platforms VMS

  Location http://www.openvms.compaq.com/freeware/CMEM/

  Overview Provides debugging versions of the C run-time library memory allocation routines, with support for stack tracebacks and page protection.

- CSRI malloc

  Author Mark Moraes (moraes@deshaw.com)

  License Free Software

  Platforms Various UNIX

  Location ftp://ftp.cs.toronto.edu/pub/moraes/malloc.tar.gz

  Overview A library of dynamic memory allocation functions with limited debugging and profiling support and detection of memory leaks. Also comes with a graphical tool to display a dynamic picture of the heap.

- Dbmalloc

  Author Conor P. Cahill (cpcahil@virtech.vti.com)

  License Free Software

Platforms Various UNIX

Location http://dickey.his.com/dbmalloc/dbmalloc.html

Overview Provides replacements for memory management library functions and provides a full set of debugging features which detect memory overruns and other types of misuse.

- Dbmalloc

  Author Michael McTernan (mm7323@bris.ac.uk)

  License Free Software

  Platforms Various UNIX, Windows

  Location http://www.cs.bris.ac.uk/~mm7323/DbMalloc/

  Overview A drop-in replacement for the C memory allocation functions, providing facilities for quickly finding memory leaks.

- Debauch

  Author Jon A. Christopher (jac8792@tamu.edu)

  License GNU General Public License

  Platforms Linux

  Location http://mackerel.tamu.edu/jon/gnu/

  Overview A memory allocation debugger for C which will detect memory leaks, corrupted memory, stores to freed memory and more.

- Debug Heap

  Author IBM Corporation (info@ibm.com)

  License Commercial Software

  Platforms IBM AS/400

  Location http://www.as400.ibm.com/developer/porting/heapexternal.html

  Overview A heap debugging environment with stack traceback for IBM AS/400 servers.

- DebugObject

  Author Beniamin Cherniavsky (cben@israel.crosswinds.net)

  License GNU General Public License

  Platforms Various UNIX, Windows

  Location http://www.crosswinds.net/~cben/objc/

  Overview A set of classes for debugging dynamic memory problems in Objective C.

- Dmalloc

  Author Gray Watson (gray@burger.letters.com)

  License Free Software

  Platforms Various UNIX, Windows, MS-DOS

  Location http://www.dmalloc.com/

  Overview A drop-in replacement for the system's memory management routines, providing powerful debugging facilities configurable at run-time. Formerly known as Malloc_Dbg.

- DPCRTLMM

  Author David Duncan Ross Palmer (overlord@daybologic.co.uk)

  License GNU General Public License

  Platforms Windows, DOS

  Location http://daybologic.com/Dev/dpcrtlmm/

  Overview Detects failures to release memory and attempts to release memory which has not been allocated, and can also provide statistics and logging facilities.

- Electric Fence

  Author Bruce Perens (bruce@pixar.com)

  License GNU General Public License

  Platforms Various UNIX

  Location ftp://ftp.perens.com/pub/ElectricFence/

  Overview Uses virtual memory hardware to protect dynamically allocated memory in order to detect illegal memory accesses.

- Enforcer

  Author Michael Sinz (Enforcer@sinz.org)

  License Free Software

  Platforms AmigaOS

  Location http://www.iam.com/amiga/enforcer.html

  Overview Sets up MMU tables to watch for illegal accesses to memory, such as the low page and non-existent pages.

- FDA (Free Debug Allocator)

  Author Thomas Helvey (tomh@inxpress.net)

  License GNU General Public License

  Platforms Linux, Windows

  Location http://www.debian.org/Packages/unstable/devel/fda.html

  Overview Provides routines that can be plugged in to replace `malloc()`, `calloc()`, `realloc()` and `free()`.

- Fortify

  Author Simon Bullen (sbullen@cybergraphic.com.au)

  License Free Software

  Platforms AmigaOS

  Location http://www.geocities.com/SiliconValley/Horizon/8596/fortify.html

  Overview Provides a fortified shell for memory allocations, trapping memory leaks, writes beyond and before memory blocks and writes to freed memory.

- Gabe's Debug Library

  Author Gabriel Sechan gsechan@hotmail.com

License Free Software

Platforms Windows

Location http://sourceforge.net/projects/debuglib/

Overview A debugging library for C++ which performs dynamic memory management and looks for potential problems and memory leaks.

- GC (Garbage Collector)

  Author Hans-J. Boehm (boehm@acm.org)

  License Free Software

  Platforms Various UNIX, AmigaOS, Windows, MS-DOS, MacOS

  Location http://www.hpl.hp.com/personal/Hans_Boehm/gc/

  Overview A general-purpose, garbage-collecting storage allocator that is intended to be used as a plug-in replacement for `malloc()`, but can also be used to detect memory leaks.

- GlowCode

  Author Electric Software, Inc. (info@glowcode.com)

  License Commercial Software

  Platforms Windows

  Location http://www.glowcode.com/

  Overview Provides a profiler, call coverage tool and resource browser which can detail memory leaks.

- Great Circle

  Author Geodesic Systems (info@geodesic.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.geodesic.com/

  Overview Provides complete heap profiling, allowing programmers to see what parts of a program are using the most memory with symbolic stack tracing.

- HeapAgent

  Author MicroQuill (info@microquill.com)

  License Commercial Software

  Platforms Windows

  Location http://www.microquill.com/

  Overview Instruments the heap to provide heap error detection without the need to recompile any source code.

- HeapCheck

  Author Thanassis Tsiodras (ttsiod@softlab.ntua.gr)

  License GNU General Public License

  Platforms Windows

Location http://www.image.ece.ntua.gr/~ttsiod/HeapCheck.html

Overview A debugging memory allocator that can detect invalid read/write accesses to heap memory, and also detects memory leaks.

- HeapManager

  Author Andrew Wulf (heapmanager@biit.com)

  License Free Software

  Platforms MacOS

  Location http://www.biit.com/

  Overview Provides a general-purpose dynamic memory allocation debugging package with symbolic stack traceback.

- Insure++

  Author ParaSoft (info@parasoft.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.parasoft.com/

  Overview Uses Source Code Instrumentation and Runtime Pointer Tracking technologies to pinpoint memory corruption, memory leaks, operations on unrelated pointers and more. The Inuse graphical memory usage display tool is also provided with this software.

- JMalloc

  Author Jeff Dunlop

  License Free Software

  Platforms Windows, MS-DOS

  Location http://www.snippets.org/

  Overview Provides tracing and debugging for `malloc()` and `operator new`.

- JProbe

  Author KL Group (info@klgroup.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.klgroup.com/

  Overview Helps pinpoint memory leaks in Java applications by tracking which objects hold references to other objects, and allows visualisation of memory usage in real-time.

- Leak

  Author Christopher Phillips (pefv700@hermes.chpc.utexas.edu)

  License Free Software

  Platforms Various UNIX

  Location http://sources.isc.org/devel/memleak/leak.txt

Overview Logs all calls to `malloc()` and related functions to database files with the filename and line number, then attempts to validate reallocations and deallocations and detect memory leaks.

- Leak

  Author Josh McCormick (jmccorm@galstar.com)

  License Free Software

  Platforms Various UNIX

  Location http://www.galstar.com/~jmccorm/leak/

  Overview A simple shell script that monitors the system looking for processes which leak memory.

- Leakers

  Author Gabriel M. Deal (gmd@yellowleaf.org)

  License GNU General Public License

  Platforms Various UNIX

  Location http://www.yellowleaf.org/gmd/software/leakers/

  Overview Detects memory allocation errors by writing a log file and then examining it for memory leaks and attempts to free memory multiple times.

- LeakTracer

  Author Erwin Andreasen (erwin@andreasen.org)

  License Free Software

  Platforms Various UNIX

  Location http://www.andreasen.org/LeakTracer/

  Overview Detects memory leaks in C++ programs by overriding `operator new` and `operator delete`.

- Leaky

  Author Kipp Hickman (kipp@netscape.com)

  License Netscape Public License

  Platforms Linux

  Location http://www.mozilla.org/unix/leaky.html

  Overview A program which helps find memory leaks and helps debug reference count problems with xpcom objects.

- LibKmalloc

  Author Akira Higuchi (a@kondara.org)

  License GNU General Public License

  Platforms Linux

  Location http://www.kondara.org/~a/libkmalloc.html

  Overview A tiny malloc debugger which detects multiple frees and buffer overruns and underruns.

- LibSafe

  Author AT&T Bell Labs (libsafe@research.bell-labs.com)

  License GNU General Public License

  Platforms Linux

  Location http://www.bell-labs.com/org/11356/libsafe.html

  Overview Protects a process against the exploitation of buffer overflow vulnerabilities in process stacks.

- Malloc Debug

  Author Brandon S. Allbery allbery@ncoast.org

  License Free Software

  Platforms Various UNIX

  Location http://www.leo.org/pub/comp/usenet/comp.sources.misc/malloc-debug/

  Overview A debugging malloc package with stack traceback capability.

- Malloc Debug Library

  Author Rammi (rammi@quincunx.escape.de)

  License Free Software

  Platforms Various UNIX

  Location http://www.escape.de/users/quincunx/rmdebug.html

  Overview Implements wrappers for the normal heap handling functions.

- MallocTrace

  Author Mark Brader (msb@sq.sq.com)

  License Free Software

  Platforms Various UNIX

  Location ftp://ftp.uu.net/usenet/comp.sources.unix/volume18/malloc-trace.Z

  Overview A malloc package with call stack tracebacks.

- MalTrace

  Author Michael Schwartz (schwartz@cs.washington.edu)

  License Free Software

  Platforms Various UNIX

  Location http://www.mit.edu/afs/sipb/user/tytso/News/maltrace

  Overview Traces all calls to `malloc()` and `free()` in order to detect memory leaks.

- MCheck

  Author Ronald Veldema (rveldema@cs.vu.nl)

  License GNU General Public License

  Platforms Linux

  Location http://www.cs.vu.nl/~rveldema/mcheck/mcheck.html

Overview A memory usage and malloc checker for C and C++. Comes with a Java application for browsing the trace files produced.

- MEM

  Author Walter Bright

  License Free Software

  Platforms MS-DOS

  Location http://www.snippets.org/

  Overview A set of functions for debugging pointer and memory allocation problems.

- MemCheck

  Author Stratosware Corporation (info@stratosware.com)

  License Commercial Software

  Platforms Windows

  Location http://www.stratosware.com/

  Overview Detects various run-time errors related to operating system resources and provides information on memory leaks.

- MemCheck

  Author IBM Corporation (info@ibm.com)

  License Commercial Software

  Platforms IBM OS/390

  Location http://www.s390.ibm.com/oe/tools/memcheck_2_1.html

  Overview Aids the discovery of memory leaks in single- and multi-threaded C/C++ programs.

- MemDebug

  Author Rene Schmit (rene.schmit@bss.lu)

  License Free Software

  Platforms Various UNIX, Windows, MS-DOS, MacOS

  Location http://www.bss.lu/Memdebug/Memdebug.html

  Overview Provides memory management error detection, memory usage error detection, memory usage profiling and error simulation.

- MemLeak

  Author Keith Packard (keithp@ncd.com)

  License Free Software

  Platforms Various UNIX

  Location ftp://ftp.x.org/pub/R6.4/xc/util/memleak/

  Overview Replaces the C library allocation functions and provides extensive memory checking, locating lost memory, detecting free memory still in use and stores to free memory along with stack tracebacks.

- Memory Advisor

Author PLATINUM Technology (info@platinum.com)

License Commercial Software

Platforms Various UNIX

Location http://www.platinum.com/

Overview Disassembles an object module into system-independent assembler code, inserts error checking instructions, then re-assembles the code. Can also replace existing malloc libraries in order to provide greater error checking. Formerly known as Sentinel.

- Memory Sleuth

  Author TurboPower (info@turbopower.com)

  License Commercial Software

  Platforms Windows

  Location http://www.turbopower.com/

  Overview Quickly tracks down memory leaks and resource allocation errors with C++Builder and Delphi.

- Memprof

  Author Owen Taylor (otaylor@redhat.com)

  License GNU General Public License

  Platforms Linux

  Location http://people.redhat.com/otaylor/memprof/

  Overview A tool for profiling memory usage and detecting memory leaks.

- Memproof

  Author AutomatedQA (info@totalqa.com)

  License Free Software

  Platforms Windows

  Location http://www.totalqa.com/

  Overview A memory and resource leak debugger for Borland's family of Windows compilers.

- MemTest

  Author Jim Buchanan (jbuchana@iquest.net)

  License Free Software

  Platforms Various UNIX

  Location ftp://ftp.loxinfo.co.th/pub/unix/utils/mem_test-0_10_tar.gz

  Overview Helps locate memory leaks in a program under development by creating a log file that records most memory allocations and deallocations.

- MemTrace

  Author Nico Hoogervorst (nico@knoware.nl)

  License Free Software

Platforms Windows

Location http://utopia.knoware.nl/users/nico/tools/c/memtrace/

Overview A simple enhancement for C source code which makes it easier to find memory leaks.

- MemWatch

  Author Johan Lindh (johan@link-data.com)

  License Free Software

  Platforms Various UNIX, Windows

  Location http://www.link-data.com/

  Overview A fault-tolerant memory leak and corruption detection tool.

- MemWatch

  Author Doug Walker (walker@unx.sas.com)

  License Free Software

  Platforms AmigaOS

  Location http://wuarchive.wustl.edu/~aminet/dirs/dev_debug.html

  Overview Provides replacement memory allocation routines for adding lots of memory debugging features that you link into your program.

- MM (Shared Memory Library)

  Author Ralf S. Engelschall (rse@engelschall.com)

  License Free Software

  Platforms Various UNIX, Windows

  Location http://www.engelschall.com/sw/mm/

  Overview Simplifies the usage (and can help debug) the use of shared memory between related processes.

- MM

  Author Dave Clements (clements@cs.uoregon.edu)

  License Free Software

  Platforms Various UNIX

  Location http://www.cirl.uoregon.edu/clements/memoryManager.html

  Overview Overrides the C dynamic memory allocation functions to provide better debugging capabilities.

- Mmalloc

  Author Mike Haertel (mike@ai.mit.edu) and Fred Fish (fnf@cygnus.com)

  License GNU General Public License

  Platforms Various UNIX

  Location http://www.gnu.org/

  Overview Uses `mmap()` to allocate separate pools of memory which can be mapped onto files for later reuse.

- MPR

  Author Taj Khattra (taj.khattra@pobox.com)

  License Free Software

  Platforms Linux

  Location http://metalab.unc.edu/pub/Linux/devel/lang/c/mpr-2.0.tar.gz

  Overview Attempts to find memory leaks in C/C++ programs by writing a log file during program execution, which can then be processed for obtaining further information.

- Mprof

  Author Ben Zorn (zorn@microsoft.com)

  License Free Software

  Platforms Various UNIX

  Location ftp://gatekeeper.dec.com/pub/misc/mprof-3.0.tar.Z

  Overview Profiles the dynamic memory allocation behaviour of programs by logging details for each function than makes a memory allocation, including call stack tracebacks.

- MSS (Memory Supervision System)

  Author Juan Jesus Alcolea Picazo (a920101@zipi.fi.upm.es) and Peter Palotas (blizzar@hem1.passagen.se)

  License GNU General Public License

  Platforms Linux, Windows, MS-DOS

  Location http://hem.passagen.se/blizzar/mss/

  Overview Full-featured malloc library for C and C++ providing detection of memory leaks, use of uninitialised memory and out of range block accesses as well as lots of tracing facilities.

- MTrace

  Author Morris R. Dovey (mrdovey@iedu.com)

  License Free Software

  Platforms Various UNIX, Windows

  Location http://www.iedu.com/mrd/c/mtrace.c

  Overview A very simple malloc tracing package.

- MuForce

  Author Thomas Richter (thor@einstein.math.tu-berlin.de)

  License Free Software

  Platforms AmigaOS

  Location http://www.math.tu-berlin.de/~thor/thor/index.html

  Overview Uses the MMU to monitor the system for any writes to non-existent memory and reports them over the serial port or any other output stream.

- MuGuardianAngel

  Author Thomas Richter (thor@einstein.math.tu-berlin.de)

  License Free Software

  Platforms AmigaOS

  Location http://www.math.tu-berlin.de/~thor/thor/index.html

  Overview An extension to the MuForce program which protects free memory and detects all illegal memory accesses.

- MuLib

  Author Thomas Richter (thor@einstein.math.tu-berlin.de)

  License Free Software

  Platforms AmigaOS

  Location http://www.math.tu-berlin.de/~thor/thor/index.html

  Overview Provides access to the MMU in modern Amigas so that features such as virtual memory can be implemented.

- MULTI

  Author Green Hills Software, Inc. (sales@ghs.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.ghs.com

  Overview Inserts special checks into a program to watch for and report a broad variety of run-time errors, including freeing unallocated memory and memory leaks.

- Mungwall

  Author Commodore-Amiga, Inc. (info@amiga.de)

  License Free Software

  Platforms AmigaOS

  Location http://wuarchive.wustl.edu/~aminet/dirs/dev_debug.html

  Overview Patches the system to check for free memory corruption.

- NJAMD (Not Just Another Malloc Debugger)

  Author Mike Perry (mikepery@fscked.org)

  License GNU General Public License

  Platforms Various UNIX

  Location http://fscked.org/proj/njamd.shtml/

  Overview Helps track down a wide range of memory allocation problems and is divided into a front end executable and a library back end.

- ObjectCenter

  Author CenterLine Development Systems (info@centerline.com)

  License Commercial Software

Platforms Various UNIX

Location http://www.centerline.com/

Overview Provides a C and C++ programming environment that can detect memory leaks, duplicate frees and illegal access errors including loads from uninitialised objects.

- Optimizeit

  Author Intuitive Systems, Inc. (info@optimizeit.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.optimizeit.com/

  Overview Attempts to locate memory leaks and performance bottlenecks in Java programs.

- Plumber

  Author Owen O'Malley (omalley@ics.uci.edu)

  License GNU General Public License

  Platforms Linux, Solaris, SunOS

  Location http://www.ics.uci.edu/~softtest/plumber.html

  Overview A tool that replaces the normal Ada and C/C++ dynamic memory allocation functions and detects unfreed memory blocks.

- Purify

  Author Rational Software (info@rational.com)

  License Commercial Software

  Platforms Various UNIX, Windows

  Location http://www.rational.com/

  Overview Uses Object Code Insertion technology to provide run-time error checking and memory leak detection.

- QC

  Author Onyx Technology (sales@onyx-tech.com)

  License Commercial Software

  Platforms MacOS

  Location http://www.onyx-tech.com/

  Overview Runs in the background as a control panel and detects various memory errors which can then be caught and run under a debugger.

- SBase

  Author Ben Lilburne (blilburn@cit.nepean.uws.edu.au)

  License Free Software

  Platforms Various UNIX, Windows

  Location http://www.cit.uws.edu.au/~blilburn/sbase/

Overview A set of classes for debugging dynamic memory problems in Objective C.

- SmartAlloc

  Author John Walker

  License Free Software

  Platforms Various UNIX, MS-DOS

  Location http://www.fourmilab.ch/smartall/

  Overview Detects orphaned buffers of dynamic memory allocations and also helps to find other common problems in management of dynamic storage.

- SmartHeap

  Author MicroQuill (info@microquill.com)

  License Commercial Software

  Platforms Various UNIX, Windows, OS/2, MS-DOS, MacOS

  Location http://www.microquill.com/

  Overview Provides optimised heap performance along with detecting memory leaks, memory overwrites, double-freeing, wild pointers, invalid parameters, etc.

- Spotlight

  Author Onyx Technology (sales@onyx-tech.com)

  License Commercial Software

  Platforms MacOS

  Location http://www.onyx-tech.com/

  Overview Performs memory protection on PowerPC executables and helps detect memory leaks.

- StackTrace

  Author Bjorn Reese (breese@mail1.stofanet.dk)

  License Free Software

  Platforms Various UNIX

  Location http://home1.stofanet.dk/breese/debug/debug.tar.gz

  Overview Provides code to generate a stack trace of the program at any point during execution using either a debugger or built-in methods found in the GNU C compiler or on some systems.

- TestCenter

  Author CenterLine Development Systems (info@centerline.com)

  License Commercial Software

  Platforms Various UNIX

  Location http://www.centerline.com/

  Overview Detects memory leaks, duplicate frees and illegal access errors including loads from uninitialised objects.

- Third Degree

  Author Digital Equipment Corporation (info@digital.com)

  License Commercial Software

  Platforms Digital UNIX

  Location http://www.digital.com/

  Overview A tool that performs memory access checks and memory leak detection of C, C++ and Fortran programs at run-time. Applications are modified using ATOM to determine if any memory locations are accessed when not properly allocated or initialised.

- Vmalloc

  Author Kiem-Phong Vo (kpv@research.att.com)

  License AT&T Source Code License

  Platforms Various UNIX, Windows

  Location http://akpublic.research.att.com/sw/tools/vmalloc/

  Overview A discipline and method library for dynamic memory allocation, with support for regions, debugging and profiling.

- Wipeout

  Author Olaf Barthel (olsen@sourcery.han.de)

  License Free Software

  Platforms AmigaOS

  Location http://wuarchive.wustl.edu/~aminet/dirs/dev_debug.html

  Overview Runs in the background checking free memory for corruption.

- YaMa

  Author Venkatesha Murthy G. (gvmt@vsnl.com)

  License Free Software

  Platforms Linux

  Location http://www.geocities.com/ipsgvm/libyama/

  Overview A memory allocator with leak tracing and some anti-heap corruption facilities.

- YAMD (Yet Another Malloc Debugger)

  Author Nate Eldredge (neldredge@hmc.edu)

  License GNU General Public License

  Platforms Linux, MS-DOS

  Location http://www3.hmc.edu/~neldredge/yamd/

  Overview A tool for finding bugs related to dynamic memory allocation in C and C++, and includes paging mechanisms to catch bugs immediately.

- ZeroFault

  Author The Kernel Group (info@zerofault.com)

License
: Commercial Software

Platforms
: AIX UNIX

Location
: http://www.zerofault.com/

Overview
: Uses run-time emulator technology to provide run-time error checking and memory leak detection.

However, before you try out any of the above software, there may already be a malloc library with debugging support on your system that might be suitable for solving your problem. For example, on Solaris the following libraries are available:

malloc(3c)
: Trade-off between performance and efficiency.

malloc(3x)
: Slower performance, space-efficient.

bsdmalloc(3x)
: Better performance, space-inefficient.

mtmalloc(3t)
: Thread-safe memory allocator.

mapmalloc(3x)
: Uses `mmap()` instead of `sbrk()` to allocate heap space.

watchmalloc(3x)
: Uses watch point areas to check for overflows.

On platforms with the GNU C library, such as Linux, there are several environment variables that can be used to enable various debugging features of `malloc()`, etc. There are also extra functions provided in the library which can be used to aid in debugging, and some shell scripts which can translate return addresses or locate unfreed memory allocations in the log files produced. Useful information on the debugging features available within the GNU C library is located at http://sdb.suse.de/sdb/en/html/aj_debug.html.

If you suspect that the debugging problem you are looking at is likely to be related to UNIX system calls then some systems come with the `strace` or `truss` commands which allow you to trace all of the system calls that a program makes when running. This can sometimes be invaluable in pinpointing the exact point at which a program fails, but as it only operates at the system call level, no information about individual memory allocations is available.

Appendix K References

This section contains references to interesting papers and resources on related topics and the field of memory management in general. The vast majority of theoretical information can be found at the Memory Management Reference, although this does tend to concentrate on garbage collection. The other references take a more practical approach to memory management and in some cases provide implementation details. Let me know if you'd like to see any other references or resources added to this list.

- Avoiding Motif Memory Leaks

  Author Kenton Lee (kenton@rahul.net)

  Location http://www.rahul.net/kenton/txa/mar96.html

  Overview An article on avoiding memory leaks in Motif applications.

- Effective C++ Memory Allocation

  Author Aaron Dailey (adailey@chaparraltec.com)

  Location http://www.embedded.com/1999/9901/9901feat2.htm

  Overview Documents techniques for better use of the C++ dynamic memory allocation operators.

- A Memory Allocator

  Author Doug Lea (dl@gee.cs.oswego.edu)

  Location http://gee.cs.oswego.edu/dl/html/malloc.html

  Overview Information on general memory allocation principles.

- The Memory Management Reference

  Author XANALYS Software Tools (mm-web@xanalys.com)

  Location http://www.xanalys.com/software_tools/mm/

  Overview Links to many documents and research papers in the field of memory management, and has a large glossary which lists and explains related terms.

- My Rant on C++'s `operator new`

  Author David Mazieres (dm@cs.nyu.edu)

  Location http://www.pdos.lcs.mit.edu/~dm/c++-new.html

  Overview Provides a scathing critique on the C++ dynamic memory allocation operators.

- The Virtual Memory Tutorial

  Author The Hyperlearning Center (webmaster@cne.gmu.edu)

  Location http://www.cne.gmu.edu/modules/vm/

  Overview Provides a comprehensive tutorial on virtual memory, as well as detailing its history, theory and implementation.

- X Window System Memory Leaks and Other Memory Bugs

  Author Kenton Lee (kenton@rahul.net)

  Location http://www.rahul.net/kenton/txa/feb96.html

  Overview An article on debugging memory problems in X applications.

Appendix L Copying

GNU LIBRARY GENERAL PUBLIC LICENSE
Version 2, June 1991

[This is the first released version of the library GPL. It is
numbered 2 because it goes with version 2 of the ordinary GPL.]

Preamble

The licenses for most software are designed to take away your freedom to share and change it. By contrast, the GNU General Public Licenses are intended to guarantee your freedom to share and change free software--to make sure the software is free for all its users.

This license, the Library General Public License, applies to some specially designated Free Software Foundation software, and to any other libraries whose authors decide to use it. You can use it for your libraries, too.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things.

To protect your rights, we need to make restrictions that forbid anyone to deny you these rights or to ask you to surrender the rights. These restrictions translate to certain responsibilities for you if you distribute copies of the library, or if you modify it.

For example, if you distribute copies of the library, whether gratis or for a fee, you must give the recipients all the rights that we gave you. You must make sure that they, too, receive or can get the source code. If you link a program with the library, you must provide complete object files to the recipients so that they can relink them with the library, after making changes to the library and recompiling it. And you must show them these terms so they know their rights.

Our method of protecting your rights has two steps: (1) copyright the library, and (2) offer you this license which gives you legal permission to copy, distribute and/or modify the library.

Also, for each distributor's protection, we want to make certain that everyone understands that there is no warranty for this free library. If the library is modified by someone else and passed on, we want its recipients to know that what they have is not the original version, so that any problems introduced by others will not reflect on the original authors' reputations.

Finally, any free program is threatened constantly by software patents. We wish to avoid the danger that companies distributing free software will individually obtain patent licenses, thus in effect transforming the program into proprietary software. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.

Most GNU software, including some libraries, is covered by the ordinary GNU General Public License, which was designed for utility programs. This license, the GNU Library General Public License, applies to certain designated libraries. This license is quite different from the ordinary one; be sure to read it in full, and don't assume that anything in it is the same as in the ordinary license.

The reason we have a separate public license for some libraries is that they blur the distinction we usually make between modifying or adding to a program and simply using it. Linking a program with a library, without changing the library, is in some sense simply using the library, and is analogous to running a utility program or application program. However, in a textual and legal sense, the linked executable is a combined work, a derivative of the original library, and the ordinary General Public License treats it as such.

Because of this blurred distinction, using the ordinary General Public License for libraries did not effectively promote software sharing, because most developers did not use the libraries. We concluded that weaker conditions might promote sharing better.

However, unrestricted linking of non-free programs would deprive the users of those programs of all benefit from the free status of the libraries themselves. This Library General Public License is intended to permit developers of non-free programs to use free libraries, while preserving your freedom as a user of such programs to change the free libraries that are incorporated in them. (We have not seen how to achieve this as regards changes in header files, but we have achieved it as regards changes in the actual functions of the Library.) The hope is that this will lead to faster development of free libraries.

The precise terms and conditions for copying, distribution and modification follow. Pay close attention to the difference between a "work based on the library" and a "work that uses the library". The former contains code derived from the library, while the latter only works together with the library.

Note that it is possible for a library to be covered by the ordinary General Public License rather than by this special one.

```
                  GNU LIBRARY GENERAL PUBLIC LICENSE
   TERMS AND CONDITIONS FOR COPYING, DISTRIBUTION AND MODIFICATION

  0. This License Agreement applies to any software library which
contains a notice placed by the copyright holder or other authorized
party saying it may be distributed under the terms of this Library
General Public License (also called "this License").  Each licensee is
addressed as "you".

  A "library" means a collection of software functions and/or data
prepared so as to be conveniently linked with application programs
(which use some of those functions and data) to form executables.

  The "Library", below, refers to any such software library or work
which has been distributed under these terms.  A "work based on the
Library" means either the Library or any derivative work under
copyright law: that is to say, a work containing the Library or a
portion of it, either verbatim or with modifications and/or translated
straightforwardly into another language.  (Hereinafter, translation is
included without limitation in the term "modification".)

  "Source code" for a work means the preferred form of the work for
making modifications to it.  For a library, complete source code means
all the source code for all modules it contains, plus any associated
interface definition files, plus the scripts used to control compilation
and installation of the library.

  Activities other than copying, distribution and modification are not
covered by this License; they are outside its scope.  The act of
running a program using the Library is not restricted, and output from
such a program is covered only if its contents constitute a work based
on the Library (independent of the use of the Library in a tool for
writing it).  Whether that is true depends on what the Library does
and what the program that uses the Library does.

  1. You may copy and distribute verbatim copies of the Library's
complete source code as you receive it, in any medium, provided that
you conspicuously and appropriately publish on each copy an
appropriate copyright notice and disclaimer of warranty; keep intact
all the notices that refer to this License and to the absence of any
warranty; and distribute a copy of this License along with the
Library.

  You may charge a fee for the physical act of transferring a copy,
and you may at your option offer warranty protection in exchange for a
fee.

  2. You may modify your copy or copies of the Library or any portion
of it, thus forming a work based on the Library, and copy and
distribute such modifications or work under the terms of Section 1
above, provided that you also meet all of these conditions:
```

a) The modified work must itself be a software library.

b) You must cause the files modified to carry prominent notices stating that you changed the files and the date of any change.

c) You must cause the whole of the work to be licensed at no charge to all third parties under the terms of this License.

d) If a facility in the modified Library refers to a function or a table of data to be supplied by an application program that uses the facility, other than as an argument passed when the facility is invoked, then you must make a good faith effort to ensure that, in the event an application does not supply such function or table, the facility still operates, and performs whatever part of its purpose remains meaningful.

(For example, a function in a library to compute square roots has a purpose that is entirely well-defined independent of the application. Therefore, Subsection 2d requires that any application-supplied function or table used by this function must be optional: if the application does not supply it, the square root function must still compute square roots.)

These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Library, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Library, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Library.

In addition, mere aggregation of another work not based on the Library with the Library (or with a work based on the Library) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

3. You may opt to apply the terms of the ordinary GNU General Public License instead of this License to a given copy of the Library. To do this, you must alter all the notices that refer to this License, so that they refer to the ordinary GNU General Public License, version 2, instead of to this License. (If a newer version than version 2 of the ordinary GNU General Public License has appeared, then you can specify

that version instead if you wish.) Do not make any other change in these notices.

Once this change is made in a given copy, it is irreversible for that copy, so the ordinary GNU General Public License applies to all subsequent copies and derivative works made from that copy.

This option is useful when you wish to copy part of the code of the Library into a program that is not a library.

4. You may copy and distribute the Library (or a portion or derivative of it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you accompany it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange.

If distribution of object code is made by offering access to copy from a designated place, then offering equivalent access to copy the source code from the same place satisfies the requirement to distribute the source code, even though third parties are not compelled to copy the source along with the object code.

5. A program that contains no derivative of any portion of the Library, but is designed to work with the Library by being compiled or linked with it, is called a "work that uses the Library". Such a work, in isolation, is not a derivative work of the Library, and therefore falls outside the scope of this License.

However, linking a "work that uses the Library" with the Library creates an executable that is a derivative of the Library (because it contains portions of the Library), rather than a "work that uses the library". The executable is therefore covered by this License. Section 6 states terms for distribution of such executables.

When a "work that uses the Library" uses material from a header file that is part of the Library, the object code for the work may be a derivative work of the Library even though the source code is not. Whether this is true is especially significant if the work can be linked without the Library, or if the work is itself a library. The threshold for this to be true is not precisely defined by law.

If such an object file uses only numerical parameters, data structure layouts and accessors, and small macros and small inline functions (ten lines or less in length), then the use of the object file is unrestricted, regardless of whether it is legally a derivative work. (Executables containing this object code plus portions of the Library will still fall under Section 6.)

Otherwise, if the work is a derivative of the Library, you may distribute the object code for the work under the terms of Section 6.

```
Any executables containing that work also fall under Section 6,
whether or not they are linked directly with the Library itself.

  6. As an exception to the Sections above, you may also compile or
link a "work that uses the Library" with the Library to produce a
work containing portions of the Library, and distribute that work
under terms of your choice, provided that the terms permit
modification of the work for the customer's own use and reverse
engineering for debugging such modifications.

  You must give prominent notice with each copy of the work that the
Library is used in it and that the Library and its use are covered by
this License.  You must supply a copy of this License.  If the work
during execution displays copyright notices, you must include the
copyright notice for the Library among them, as well as a reference
directing the user to the copy of this License.  Also, you must do one
of these things:

    a) Accompany the work with the complete corresponding
    machine-readable source code for the Library including whatever
    changes were used in the work (which must be distributed under
    Sections 1 and 2 above); and, if the work is an executable linked
    with the Library, with the complete machine-readable "work that
    uses the Library", as object code and/or source code, so that the
    user can modify the Library and then relink to produce a modified
    executable containing the modified Library.  (It is understood
    that the user who changes the contents of definitions files in the
    Library will not necessarily be able to recompile the application
    to use the modified definitions.)

    b) Accompany the work with a written offer, valid for at
    least three years, to give the same user the materials
    specified in Subsection 6a, above, for a charge no more
    than the cost of performing this distribution.

    c) If distribution of the work is made by offering access to copy
    from a designated place, offer equivalent access to copy the above
    specified materials from the same place.

    d) Verify that the user has already received a copy of these
    materials or that you have already sent this user a copy.

  For an executable, the required form of the "work that uses the
Library" must include any data and utility programs needed for
reproducing the executable from it.  However, as a special exception,
the source code distributed need not include anything that is normally
distributed (in either source or binary form) with the major
components (compiler, kernel, and so on) of the operating system on
which the executable runs, unless that component itself accompanies
the executable.
```

It may happen that this requirement contradicts the license restrictions of other proprietary libraries that do not normally accompany the operating system. Such a contradiction means you cannot use both them and the Library together in an executable that you distribute.

7. You may place library facilities that are a work based on the Library side-by-side in a single library together with other library facilities not covered by this License, and distribute such a combined library, provided that the separate distribution of the work based on the Library and of the other library facilities is otherwise permitted, and provided that you do these two things:

a) Accompany the combined library with a copy of the same work based on the Library, uncombined with any other library facilities. This must be distributed under the terms of the Sections above.

b) Give prominent notice with the combined library of the fact that part of it is a work based on the Library, and explaining where to find the accompanying uncombined form of the same work.

8. You may not copy, modify, sublicense, link with, or distribute the Library except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense, link with, or distribute the Library is void, and will automatically terminate your rights under this License. However, parties who have received copies, or rights, from you under this License will not have their licenses terminated so long as such parties remain in full compliance.

9. You are not required to accept this License, since you have not signed it. However, nothing else grants you permission to modify or distribute the Library or its derivative works. These actions are prohibited by law if you do not accept this License. Therefore, by modifying or distributing the Library (or any work based on the Library), you indicate your acceptance of this License to do so, and all its terms and conditions for copying, distributing or modifying the Library or works based on it.

10. Each time you redistribute the Library (or any work based on the Library), the recipient automatically receives a license from the original licensor to copy, distribute, link with or modify the Library subject to these terms and conditions. You may not impose any further restrictions on the recipients' exercise of the rights granted herein. You are not responsible for enforcing compliance by third parties to this License.

11. If, as a consequence of a court judgment or allegation of patent infringement or for any other reason (not limited to patent issues), conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not

```
excuse you from the conditions of this License.  If you cannot
distribute so as to satisfy simultaneously your obligations under this
License and any other pertinent obligations, then as a consequence you
may not distribute the Library at all.  For example, if a patent
license would not permit royalty-free redistribution of the Library by
all those who receive copies directly or indirectly through you, then
the only way you could satisfy both it and this License would be to
refrain entirely from distribution of the Library.

If any portion of this section is held invalid or unenforceable under any
particular circumstance, the balance of the section is intended to apply,
and the section as a whole is intended to apply in other circumstances.

It is not the purpose of this section to induce you to infringe any
patents or other property right claims or to contest validity of any
such claims; this section has the sole purpose of protecting the
integrity of the free software distribution system which is
implemented by public license practices.  Many people have made
generous contributions to the wide range of software distributed
through that system in reliance on consistent application of that
system; it is up to the author/donor to decide if he or she is willing
to distribute software through any other system and a licensee cannot
impose that choice.

This section is intended to make thoroughly clear what is believed to
be a consequence of the rest of this License.

  12. If the distribution and/or use of the Library is restricted in
certain countries either by patents or by copyrighted interfaces, the
original copyright holder who places the Library under this License may add
an explicit geographical distribution limitation excluding those countries,
so that distribution is permitted only in or among countries not thus
excluded.  In such case, this License incorporates the limitation as if
written in the body of this License.

  13. The Free Software Foundation may publish revised and/or new
versions of the Library General Public License from time to time.
Such new versions will be similar in spirit to the present version,
but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number.  If the Library
specifies a version number of this License which applies to it and
"any later version", you have the option of following the terms and
conditions either of that version or of any later version published by
the Free Software Foundation.  If the Library does not specify a
license version number, you may choose any version ever published by
the Free Software Foundation.

  14. If you wish to incorporate parts of the Library into other free
programs whose distribution conditions are incompatible with these,
write to the author to ask for permission.  For software which is
```

```
copyrighted by the Free Software Foundation, write to the Free
Software Foundation; we sometimes make exceptions for this.  Our
decision will be guided by the two goals of preserving the free status
of all derivatives of our free software and of promoting the sharing
and reuse of software generally.

                            NO WARRANTY

  15. BECAUSE THE LIBRARY IS LICENSED FREE OF CHARGE, THERE IS NO
WARRANTY FOR THE LIBRARY, TO THE EXTENT PERMITTED BY APPLICABLE LAW.
EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR
OTHER PARTIES PROVIDE THE LIBRARY "AS IS" WITHOUT WARRANTY OF ANY
KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE
IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR
PURPOSE.  THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE
LIBRARY IS WITH YOU.  SHOULD THE LIBRARY PROVE DEFECTIVE, YOU ASSUME
THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.

  16. IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN
WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MAY MODIFY
AND/OR REDISTRIBUTE THE LIBRARY AS PERMITTED ABOVE, BE LIABLE TO YOU
FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR
CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE
LIBRARY (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA BEING
RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A
FAILURE OF THE LIBRARY TO OPERATE WITH ANY OTHER SOFTWARE), EVEN IF
SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH
DAMAGES.

                     END OF TERMS AND CONDITIONS

           How to Apply These Terms to Your New Libraries

  If you develop a new library, and you want it to be of the greatest
possible use to the public, we recommend making it free software that
everyone can redistribute and change.  You can do so by permitting
redistribution under these terms (or, alternatively, under the terms of the
ordinary General Public License).

  To apply these terms, attach the following notices to the library.  It is
safest to attach them to the start of each source file to most effectively
convey the exclusion of warranty; and each file should have at least the
"copyright" line and a pointer to where the full notice is found.

    <one line to give the library's name and a brief idea of what it does.>
    Copyright (C) <year>  <name of author>

    This library is free software; you can redistribute it and/or
    modify it under the terms of the GNU Library General Public
    License as published by the Free Software Foundation; either
    version 2 of the License, or (at your option) any later version.
```

```
    This library is distributed in the hope that it will be useful,
    but WITHOUT ANY WARRANTY; without even the implied warranty of
    MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the GNU
    Library General Public License for more details.

    You should have received a copy of the GNU Library General Public
    License along with this library; if not, write to the Free Software
    Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307, USA

Also add information on how to contact you by electronic and paper mail.

You should also get your employer (if you work as a programmer) or your
school, if any, to sign a "copyright disclaimer" for the library, if
necessary.  Here is a sample; alter the names:

  Yoyodyne, Inc., hereby disclaims all copyright interest in the
  library ‘Frob’ (a library for tweaking knobs) written by James Random Hacker.

  <signature of Ty Coon>, 1 April 1990
  Ty Coon, President of Vice

That’s all there is to it!
```

Function index

Index

–

.

_

3

6

A

B

C

G

H

I

J

K

L

M

U

V

W

X

Y

Z