Debugging

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Debugging Scientific Applications

- Motivation for developing good debugging skills:
  - Unless you are from a new planet, you will introduce bugs at some point in your code
  - Even if you use community applications written by others, they will introduce bugs
  - And yes, commercial applications have bugs too

- Extra problems:
  - As scientific researchers, we cannot simply concern ourselves with bugs that prevent the application from running
  - We actually care deeply about the accuracy and repeatability of the result (*eg. negative density values in a flow code are probably bad)*
  - Stability is a concern (*eg. an iterative based solver that never converges*)

- The addition of strong debugging skills to your toolbox will greatly enhance your efficiency and add confidence to the numerical results

Defensive Programming Tips

- One of the best defenses against runtime bugs is to use basic defensive programming techniques:
  - Check *all* function return codes for errors
  - Check *all* input values controlling program execution to ensure they are within acceptable ranges (even those from flat text files in which you know there could not possibly be an error)

  - Echo all physical control parameters to a location that you will look at routinely (eg. *stdout*). Better yet, save all the parameters necessary to repeat an analysis in your solution files (*remember the metadata options in netCDF and HDF?)*
  - In addition to monitoring for obvious floating-point problems (eg. *divide-by-zero*), check for non-physical results in your simulations (*eg.supersonic velocities predicted in a low-speed aerodynamic simulation)*

Defensive Programming Tips

- Additional suggestions:
  - Maintain test cases for regression testing - is there an analytic test case you can benchmark against?
  - Use version control systems (git)
  - Maintain a clean, modular structure with documented interfaces: gotos, long-jumps, clever/obscure macros, etc. are dangerous over the long haul
  - Why not include some comments? Your colleagues will thank you and it just might save your dissertation when you are revisiting a tricky piece of code after a year or two
  - Strong error checking is the mark of a sage programmer and will give you more confidence in your numerical results

Defensive Programming

- Q: Isn't checking all the error codes a waste of time?
- A: It is substantially less wasteful than long debugging sessions which could have been avoided by simple error checks
- Did we mention that useful error checks are the mark of a sage programmer? - at an **absolute minimum**, please check your memory allocations (all of them, each and every time):

```
p = (float *)calloc(nnodes+1,sizeof(float));
if(p == NULL)
  {
    printf("Allocation error for p!\n");
    exit(1);
   }
```

C

```
allocate(buf(na), stat = ierror)
 if(ierror > 0) then
    print*,'ERROR: Unable to allocate array buf'
    stop
 endif
```

Fortran

Bug-a-boos

Bug Identification

- Common instances in which bugs identify themselves:
  - Build errors (Makefile, preprocessor, compiler, linker)
  - Improper memory reads/writes
    - pointer errors, array bounds overruns, unitialized memory references
    - alignment problems, exhausting memory, memory leaks
  - Misinterpretation of memory
    - Type errors, e.g. when passing parameters
    - Scope/naming errors (e.g., shadowing a global name with a local name)
  - Illegal numerical operations (divide by zero, overflow, underflow)
  - Infinite loops
  - Stack overflow
  - I/O errors
  - Logic / algorithmic errors
  - Poor performance

Bug Identification

- What are the symptoms if your application has a memory bug?
  - wrong answers derived when using values from incorrect memory space
  - application behaves differently when different levels of optimization are applied; a classic memory bug symptom is as follows:
    - you compile with full optimization (-O3 for example) and your code crashes unexpectedly
    - you disable all optimization (-O0 for example) and the code runs fine
  - adding additional print statements in the program to try and isolate the bug seems to make it disappear
  - application receives an unexpected symbol and terminates
- We need to understand what it means for our application to receive an extern signal

Signals

- A signal is an *asynchronous* event which is delivered to a process.

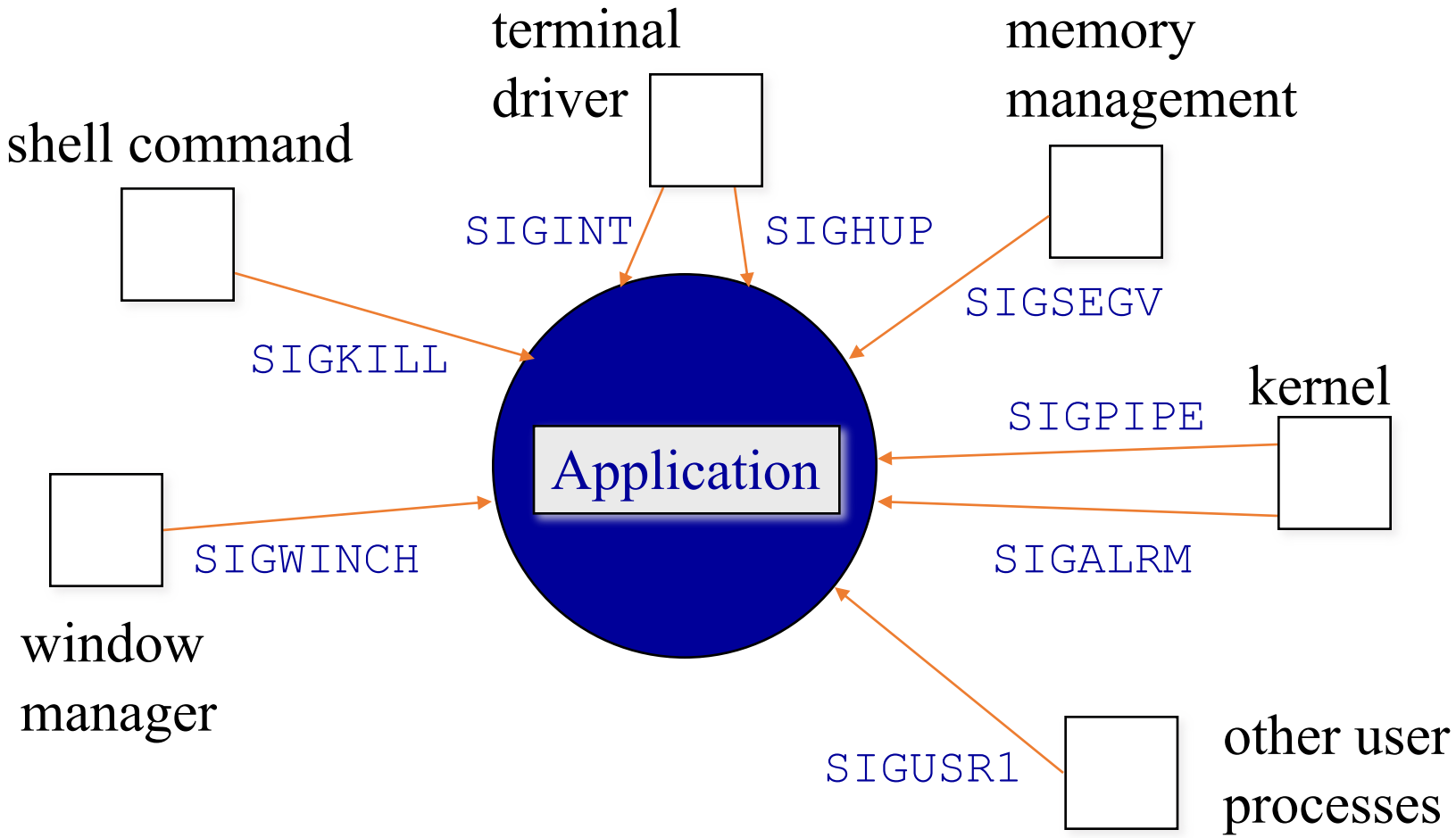
- Asynchronous means that the event can occur at any time
  - may be unrelated to the execution of the process
  - e.g. user types ctrl-C, or the operating system detects an error and sends a signal to your application

Common Signal Types

Name	*Description*	*Default Action*
`SIGINT`	Interrupt character typed	terminate process
`SIGQUIT`	Quit character typed (`^\`)	create core image
`SIGKILL`	Kill signal	terminate process
`SIGFPE`	Floating exception	create core image
`SIGSEGV`	Invalid memory reference	create core image
`SIGPIPE`	Write on pipe but no reader	terminate process
`SIGALRM`	`alarm()` clock 'rings'	terminate process
`SIGUSR1`	user-defined signal type	terminate process
`SIGUSR2`	user-defined signal type	terminate process
	:	

- See `man 7 signal` for more information

Common Signal Sources for Applications



Core Dumps

- Recall that the default action for a SIGSEGV was to create a core image and abort

- What in the world is a core image?
  - a **core dump** is a record of the raw contents of one or more regions of working memory for an application at a given time
  - commonly used to debug a program that has terminated abnormally
  - Note: if your application is "segfaulting" and you are not getting a core file, you may need to alter your shell limits. For example:

```
> unlimit coredumpsize   (tcsh)
> ulimit -c unlimited    (bash)
```

  - Main benefit of a core file is that a post-mortem analysis can be performed on an application that failed. If the symbol table was included, you can backtrace to exactly where the application when the exception occurred.

  - Note: the location of an exception may not be the original location of a bug (particularly for memory bugs)

Debugging Process

- We recognize that defensive programming can greatly reduce debugging needs, but at some point, we all must roll up our sleeves and track down a bug

- The basic steps in debugging are straightforward in principle:
  - Recognize that a bug exists
  - Isolate the source of the bug
  - Identify the cause of the bug
  - Determine a fix for the bug
  - Apply the fix and test it

- In practice, these can be difficult for particularly pesky bugs; hence, we need some more tools at our disposal (a debugger)

Standard Debuggers

- Command line debuggers are powerful tools to aid in diagnosing problematic applications and are available on all Unix architectures for C/C++ and Fortran

- Example debuggers:
  - C,C++, Fortran: gdb (or idbc with Intel compilers)
  - python: pdb or IDE
  - R: Rstudio
  - Julia: Debugger.jl

- The basic use of these debuggers is as a front-end for stepping through your application and examining variables, arrays, function returns, etc. at different times during the execution

- Gives you an opportunity to investigate the dynamic runtime behavior of the application

  Note: we will focus primarily on gdb
- The same concepts also apply to python (pdb) and R (Rstudio) debugging

Debugging Basics

- For effective debugging a couple of commands need to be mastered:
  - show program backtraces (the calling history up to the current point)
  - set breakpoints
  - display the value of individual variables
  - set new values
  - step through a program

Debugging Basics

- A breakpoint is a pseudo instruction that the user can insert at any place into the program during a debugging session
- Conceptually, the execution is controlled by the debugger and the debugger will interpret the breakpoints
- When execution crosses a breakpoint, the debugger will pause program execution so that you can:
  - inspect variables,
  - set or clear breakpoints, and
  - continue execution

Debugging Basics

- The notion of a conditional breakpoint also exists in which additional logic can be associated with the breakpoint

- When a conditional breakpoint is crossed during execution, the program will pause only if the breakpoint's break condition holds

- Example break conditions:
  - A given expression is true
  - The breakpoint has been crossed N times ("hit count") - this is very handy when you know something bad is happening on a particular iteration
  - A given expression has changed its value

Debugging Basics

- For debugging sessions, you should compile your application with extra debugging information included (eg. the symbol table)
- The symbol table maps the binary execution calls back to the original source code definitions
- To include this information, add “-g” to your compilation directives:

```
> gcc -g -o hello hello.c
```

Running GDB

- gdb is started directly from the shell
- You can include the name of the program to be debugged, and an optional core file:
  - **`gdb`**
  - **`gdb a.out`**
  - **`gdb a.out corefile`**

spawns a new instance of ./a.out

examines trapped state in corefile

- gdb can also attach to a program that is already running; you just need to know the PID associated with the desired process
  - **`gdb a.out 1134`**

useful if an application seems to be slow or stuck and you want to see what it is doing currently

gdb Basics

- Common commands for gdb:
  - run - starts the program; if you do not set up any breakpoints the program will run until it terminates or core dumps - program command line arguments can be specified here
  - print - prints a variable located in the current scope
  - next - executes the current command, and moves to the next command in the program
  - step - steps through the next command. Note: if you are at a function call, and you issue next, then the function will execute and return. However, if you issue step, then you will go to the first line of that function
  - break - sets a break point.
  - continue - used to continue till next breakpoint or termination

Note: shorthand notations exist for most of these commands: eg. 'c' = continue

gdb Basics

- More commands for gdb:
  - list - show code listing near the current execution location
  - delete - delete a breakpoint
  - condition - make a breakpoint conditional
  - display - continuously display value
  - undisplay - remove displayed value
  - where - show current function stack trace
  - help - display help text
  - quit - exit gdb

gdb Basics

- Consider the following C code for subsequent examples (hello.c):

```
#include <stdio.h>
void foo();

int main()
{
  printf("inside main\n");
  foo();
  return;
}

void foo()
{
  int i, total=0;
  printf("inside foo\n");
  for(i=0;i<1000;i++)
    total += i;
}
```

Example GDB Session

```
> gcc -g -o hello hello.c
> gdb ./hello
GNU gdb Red Hat Linux (6.3.0.0-1.134.fc5rh)
Copyright 2004 Free Software Foundation, Inc.
(gdb) run
Starting program: /home/csim/cse380/hello
inside main
inside foo


(gdb) break main
Breakpoint 1 at 0x8048384: file hello.c, line 5.
(gdb) run
Starting program: /home/csim/cse380/hello

Breakpoint 1, main () at hello.c:5
5       {
(gdb) where
#0  main () at hello.c:5
```

Example GDB Session (continued)

```
(gdb) break foo
Breakpoint 2 at 0x80483b5: file hello.c, line 13.
(gdb) cont
Continuing.
inside main

Breakpoint 2, foo () at hello.c:13
13        int i, total=0;
(gdb) list
8         return;
9       }
10
11      void foo()
12      {
13        int i, total=0;
14        printf("inside foo\n");
15        for(i=0;i<1000;i++)
16          total += i;
17      }
```

Example GDB Session (continued)

```
(gdb) cont
Continuing.
inside foo

(gdb) delete breakpoints 1 2
(gdb) break hello.c:16
Breakpoint 3 at 0x80483d1: file hello.c, line 16.
(gdb) condition 3 i==401
(gdb) run
Starting program: /home/csim/cse380/hello
inside main
inside foo
Breakpoint 3, foo () at hello.c:16
16          total += i;
(gdb) print i
$1 = 401
(gdb) where
#0  foo () at hello.c:16
#1  0x080483a6 in main () at hello.c:7
```

Floating Point Checks

- Different compilers have various options for handling floating point exceptions
- You can also check for the existence of undesirable values directly in your code (*e.g. NAN, “not-a-number”*)
- This is a good practice to test periodically in order to preemptively trap a diverged solution

Memory Debugging

- gdb and dbx are very useful for querying the runtime behavior of your application; however, it can still be difficult to trap memory errors
- Additional runtime checks and libraries are available to help in this area for C/C++ applications that utilize malloc:
  - glibc on Linux
  - dmalloc library
  - Electric Fence
  - valgrind
- The runtime checks can have a dramatic impact on performance (a slow-down of 2-50X is not unrealistic depending on the level of checking desired)
- Runtime memory checks should generally be used in a debugging/regression testing state (not for production runs)

Memory Debugging - glibc

- glibc malloc checks:
  - Recent versions of Linux libc (later than 5.4.23) and GNU libc (2.x) include a malloc implementation which is tunable via environment variables
  - When **`MALLOC_CHECK_`** is set, a special (less efficient) implementation of malloc is used which is designed to be tolerant against simple errors:
    - double calls of free() with the same argument
    - overruns of a single byte
  - Options:
    - **`MALLOC_CHECK_=0`** -> Any detected heap corruption is silently ignored
    - **`MALLOC_CHECK_=1`** -> a diagnostic is printed on stderr
    - **`MALLOC_CHECK_=2`** -> abort() is called immediately

useful in tracking original cause of a code crash

Memory Debugging - Valgrind

- Valgrind is a collection of tools for performing dynamic analysis; known for its memory-error detection tool (memcheck), but also has:
  - thread-error detection
  - cache and branch-prediction profiler
  - heap profiler
- It works by running your code on a synthetic CPU provided by the Valgrind core
  - valgrind adds its own instrumentation to the execution code
  - amount of instrumentation can vary
- Valgrind's memory error detector used in C/C++ programs for:
  - accessing memory you shouldn't
  - using undefined variables
  - memory leaks
  - incorrect freeing of memory
  - Support for Fortran, Python and R
  - Program likely to run 20-30X slower
  - No relinking required

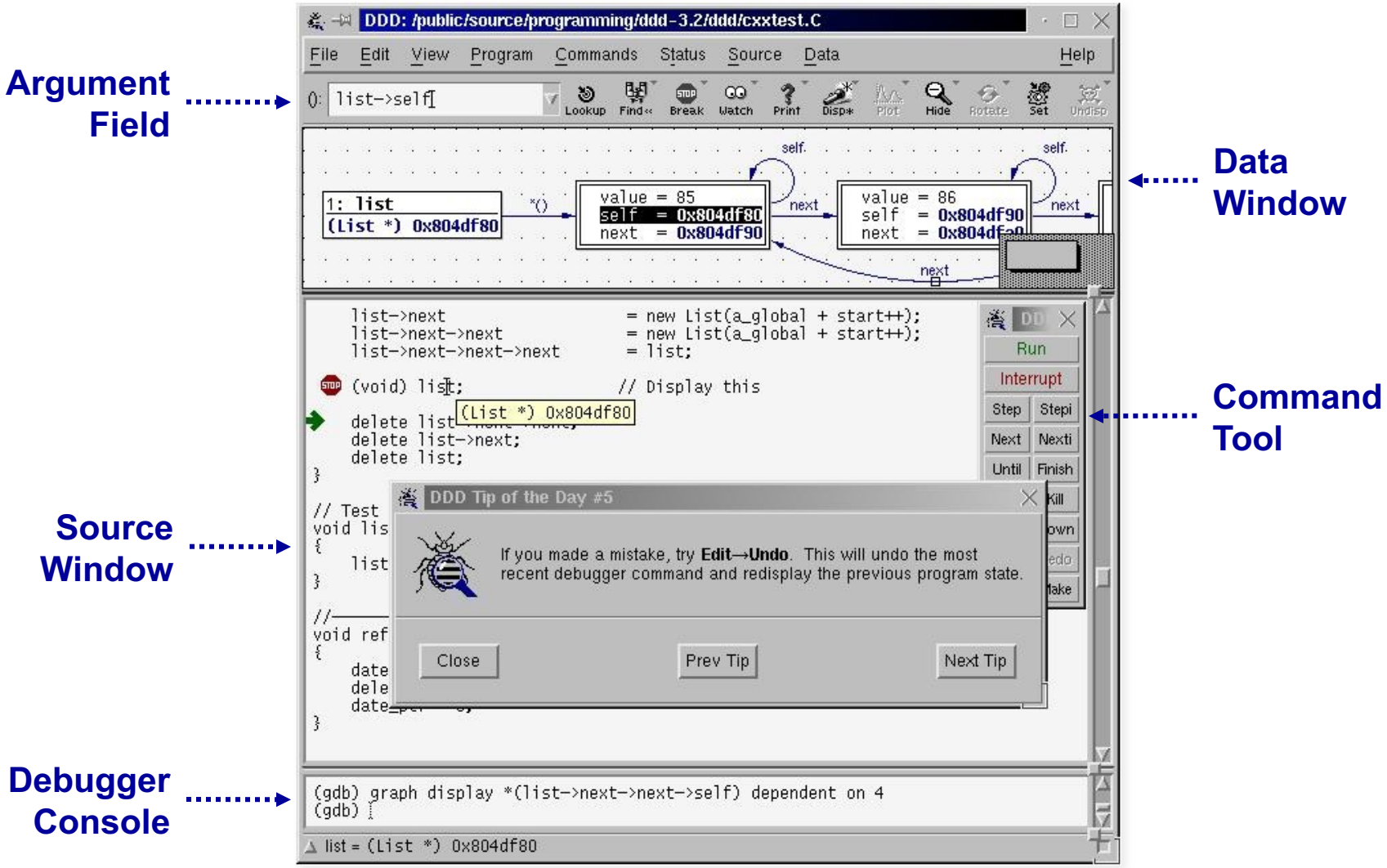
Valgrind is available on Ganymede and Europa

Graphical Debuggers

- In addition to the very capable command-line debuggers available (*gdb, dbx)* - there are graphical versions
- Once you've mastered the basic concepts with a command-line debugger, a graphical version can make your life even easier
- Common graphical debuggers:
  - DDD (*free!)*
  - TotalView (Commercial, supports threading and MPI)
  - DDT (Commercial, supports threading and MPI)
- These all require X-windows support under Unix to display the graphical interface

DDD is just a front-end
for a command-line debugger

Graphical Debugging: DDD



Graphical Debugging: DDT

- DDT is a commercial debugger for serial and parallel processing
- Available on Stampede and Lonestar
- Extremely capable
  - allows you to interrogate individual MPI tasks (with over 100K tasks)
  - includes some basic memory debugging tools (eg. overruns)
- See https://portal.tacc.utexas.edu/tutorials/ddt for usage on TACC systems