Profilers and Debuggers

Introductory Material

- First, who **doesn't** feel comfortable with assembly language?
  - You'll get to answer all the assembly questions. Yes, really.
- Lecture Style:
  - "Sit on the table" and pose questions. So, wake up!
- Lecture Goal:
  - After the lecture you'll think, "Wow, that was all really obvious. I could have done that."

One-Slide Summary

- A **debugger** helps to detect the source of a program error by **single-stepping** through the program and inspecting variable values.
- **Breakpoints** are the fundamental building block of debuggers. Breakpoints can be implemented with **signals** and special OS support.
- A **profiler** is a performance analysis tool that measures the frequency and duration of function calls as a program runs.
- Profilers can be **event-** or **sampling-based**.

Lecture Outline

- Debugging
  - Signals
  - How Debuggers Works
  - Breakpoints
  - Advanced Tools
- Profiling
  - Event-based
  - Statistical

What is a Debugger?

"A software tool that is used to detect the source of program or script errors, by performing step-by-step execution of application code and viewing the content of code variables."

-Microsoft Developer Network

Machine-Language Debugger

- Only concerned with **assembly code**
- Show instructions via disassembly
- Inspect the values of registers, memory
- Key Features (we'll explain all of them)
  - Attach to process
  - Single-stepping
  - Breakpoints
  - Conditional Breakpoints
  - Watchpoints

Signals

- A **signal** is an asynchronous notification sent to a process about an event:
  - User pressed Ctrl-C (or did **`kill %pid`**)
    - Or asked the Windows Task Manager to terminate it
  - Exceptions (divide by zero, null pointer)
  - From the OS (**`SIGPIPE`**)
- You can install a **signal handler** – a procedure that will be executed when the signal occurs.
  - Signal handlers are vulnerable to race conditions. Why?

Signal Example

```
#include <stdio.h>
#include <signal.h>

int global = 11;

int my_handler() {
  printf("In signal handler, global = %d\n",
            global);
  exit(1);
}

void main() {
  int * pointer = NULL;

  signal(SIGSEGV, my_handler) ;

  global = 33;

  * pointer = 0;

  global = 55;

  printf("Outside, global = %d\n", global);
}
```

- What does this program print?

Attaching A Debugger

- Requires operating system support
- There is a special **system call** that allows one process to act as a debugger for a target
  - What are the security concerns?
- Once this is done, the debugger can basically "catch signals" delivered to the target
  - This isn't exactly what happens, but it's a good explanation …

Building a Debugger

```
#include <stdio.h>
#include <signal.h>

#define BREAKPOINT *(0)=0

int global = 11;

int debugger_signal_handler() {
  printf("debugger prompt: \n");
  // debugger code goes here!
}

void main() {
  signal(SIGSEGV, debugger_signal_handler) ;

  global = 33;

  BREAKPOINT;

  global = 55;

  printf("Outside, global = %d\n", global);
}
```

- We can then get breakpoints and interactive debugging
  - Attach to target
  - Set up signal handler
  - Add in exception-causing instructions
  - Inspect globals, etc.

Reality

- We're not really changing the source code
- Instead, we modify the *assembly*
- We can't **insert** instructions
  - Because labels are already set at known constant offsets
- Instead we **change** them

```
 .file   "example.c"
.globl _global
        .data
        .align 4
_global:
        .long   11
        .def    ___main
        .section .rdata,"dr"
LC0:
        .ascii "Outside, global = %d\12\0"
        .text
.globl _main
        .def    _main
_main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        andl    $-16, %esp
        movl    $0, %eax
        addl    $15, %eax
        addl    $15, %eax
        shrl    $4, %eax
        sall    $4, %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        call    __alloca
        call    ___main
        movl    $33, _global
        movl    $55, _global
        movl    _global, %eax
        movl    %eax, 4(%esp)
        movl    $LC0, (%esp)
        call    _printf
        leave
        ret
        .def    _printf
```

One of the class goals is to expose you to new languages: thus x86 ASM instead of COOL-ASM.

Adding A Breakpoint

```
 .file   "example.c"
.globl _global
        .data
        .align 4
_global:
        .long   11
        .def    ___main
        .section .rdata,"dr"
LC0:
        .ascii "Outside, global = %d\12\0"
        .text
.globl _main
        .def    _main
_main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        andl    $-16, %esp
        movl    $0, %eax
        addl    $15, %eax
        addl    $15, %eax
        shrl    $4, %eax
        sall    $4, %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        call    __alloca
        call    ___main
        movl    $33, _global
        movl    $55, _global
        movl    _global, %eax
        movl    %eax, 4(%esp)
        movl    $LC0, (%esp)
        call    _printf
        leave
        ret
        .def    _printf
```

Add a breakpoint just after "global = 33;"

Storage Cell:

movl $55, _global

_main + 14

```
 .file   "example.c"
.globl _global
        .data
        .align 4
_global:
        .long   11
        .def    ___main
        .section .rdata,"dr"
LC0:
        .ascii "Outside, global = %d\12\0"
        .text
.globl _main
        .def    _main
_main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        andl    $-16, %esp
        movl    $0, %eax
        addl    $15, %eax
        addl    $15, %eax
        shrl    $4, %eax
        sall    $4, %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        call    __alloca
        call    ___main
        movl    $33, _global
        movl    $0, 0
        movl    _global, %eax
        movl    %eax, 4(%esp)
        movl    $LC0, (%esp)
        call    _printf
        leave
        ret
        .def    _printf
```

Software Breakpoint Recipe

- Debugger has already attached and set up its signal handler
- User wants a breakpoint at instruction X
- Store (X, old_instruction_at_X)
- Replace instruction at X with “*0=0”
  - Pick something illegal that’s 1 byte long
- Signal handler replaces instruction at X with stored old_instruction_at_X
- Give user interactive debugging prompt

Advanced Breakpoints

- Get register and local values by **walking the stack**
- Optimization: **hardware breakpoints**
  - Special register: if PC value = HBP register value, signal an exception
  - Faster than software, works on ROMs, only limited number of breakpoints, etc.
- Feature: **condition breakpoint**: "break at instruction X if some_variable = some_value"
- As before, but signal handler checks to see if some_variable = some_value
  - If so, present interactive debugging prompt
  - If not, return to program immediately
  - Is this fast or slow?

Single-Stepping

- Debuggers allow you to advance through code on instruction at a time
- To implement this, put a breakpoint at the first instruction (= at program start)
- The "**single step**" or "next" interactive command is equal to:
  - Put a breakpoint at the next instruction
    - +1 for COOL-ASM, +4 bytes for RISC, +X bytes for CISC, etc.
  - Resume execution

Watchpoints

- You want to know when a variable changes
- A **watchpoint** is like a breakpoint, but it stops execution whenever the value at location L changes, at any PC value
- How could we implement this?

Watchpoint Implementation

- Software Watchpoints
  - Put a breakpoint at *every instruction* (ouch!)
  - Check the current value of L against a stored value
  - If different, give interactive debugging prompt
  - If not, set next breakpoint and continue (i.e., single-step)
- Hardware Watchpoints
  - Special register holds L: if the value at address L ever changes, the CPU raises an exception

Q: Movies (284 / 842)

- Name the movie described below and **either** the general scientific theory that Malcolm invokes **or** the ambushing cold-blooded killers. In this Oscar-winning 1993 Spielberg/Crichton extravaganza involving cloning and theme parks, Dr. Ian Malcolm correctly predicts that things will not turn out well.

Q: Advertising (799 / 842)

- Name the brand most associated with instant-print self-developing photographic film and cameras. The technology was invented in 1947 by corporation founder Edwin H. Land.

Q: Cartoons (671 / 842)

- Name all five main characters and the primary automobile from **Scooby Doo, Where Are You!**

Real-World Languages

- This Northern European language boasts 5 million speakers (including Linus Torvalds). Its original writing system was devised in the 16th century from Swedish, German and Latin. Its eight vowels have powerful lexical and grammatical roles; doubled vowels do not become dipthongs.

Source-Level Debugging

- What if we want to …
  - Put a breakpoint at a *source-level* location (e.g., breakpoint at main.c line 20)
  - Single-step through *source-level* instructions (e.g., from main.c:20 to main.c:21)
  - Inspect *source-level* variables (e.g., inspect local_var, not register AX)
- We'll need the compiler's help
- How can we do it?

Debugging Information

- The compiler will emit tables
  - For every line in the program (e.g., main.c:20), what assembly instruction range does it map to?
  - For every line in the program, what variables are in scope *and where do they live* (registers, memory)?
- Put a breakpoint = table lookup
  - Put breakpoint at beginning of instruction range
- Single-step = table lookup
  - Put next breakpoint at end of instruction range +1
- Inspect value = table lookup
- Where do we put these tables?

These tables are conceptually similar to the class map or annotated AST.

How Big Are Those Tables?

```c
/* example.c */
#include <stdio.h>
#include <signal.h>

int my_global_var = 11;

void main() {

  int my_local_var = 22;

  my_local_var += my_global_var;

  printf("Outside, my_local_var = %d\n", my_local_var);
}
```

"gcc example.c"	9418 bytes
"gcc -g example.c"	23790 bytes

Debugging vs. Optimizing

- We said: the compiler will emit tables
  - For every line in the program (e.g., main.c:20), what assembly instruction range does it map to?
  - For every line in the program, what variables are in scope and where do they live (registers, memory)?

- What can go wrong if we *optimize* the program?

Replay Debugging

- Running and single-stepping are handy
- But wouldn't it be nice to go back in time?
- That is, from the current breakpoint, undo instructions in reverse order
- Intuition: functional + single assignment

x = 11;		let x_0 = 11 in
x = x + 22;		let x_1 = x_0 + 22 in
breakpoint ;	$\longrightarrow$	breakpoint ;
x = x + 33;		let x_2 = x_1 + 33 in
print x		print x

Time Travel

- **Store the state** at various times
  - time t=0 at program start
  - time t=88 after 88 instructions
  - … *why does this work?*
- When the user asks you to go back one step, you actually *go back to the last stored state* and run the program forward again with a breakpoint
  - e.g., to go back from t=150, put breakpoint at instruction 149 and re-run from t=88's state
- **ocamldebug** has this power – try it!

Valgrind

- **Valgrind** is a suite of free tools for debugging and profiling
  - Finds memory errors, profiles cache times, call graphs, profiles heap space
- It does so via *dynamic binary translation*
  - Fancy words for “it is an interpreter”
  - No need to modify, recompile or relink
  - Works with any language
- Can attach gdb to your process, etc.
- Problem: slowdown of 5x-100x
  - Rational Purify (commercial) is similar
  - Check out Strata by Jack Davidson

Valgrind Example

```
int main() {
        int some_var = 55;
        int array[10];
        int i;
        for (i=0;i<=10;i++)
                array[i] = i;
        printf("some_var = %d\n",
                some_var);
}
```

What's the output?

Valgrind Example

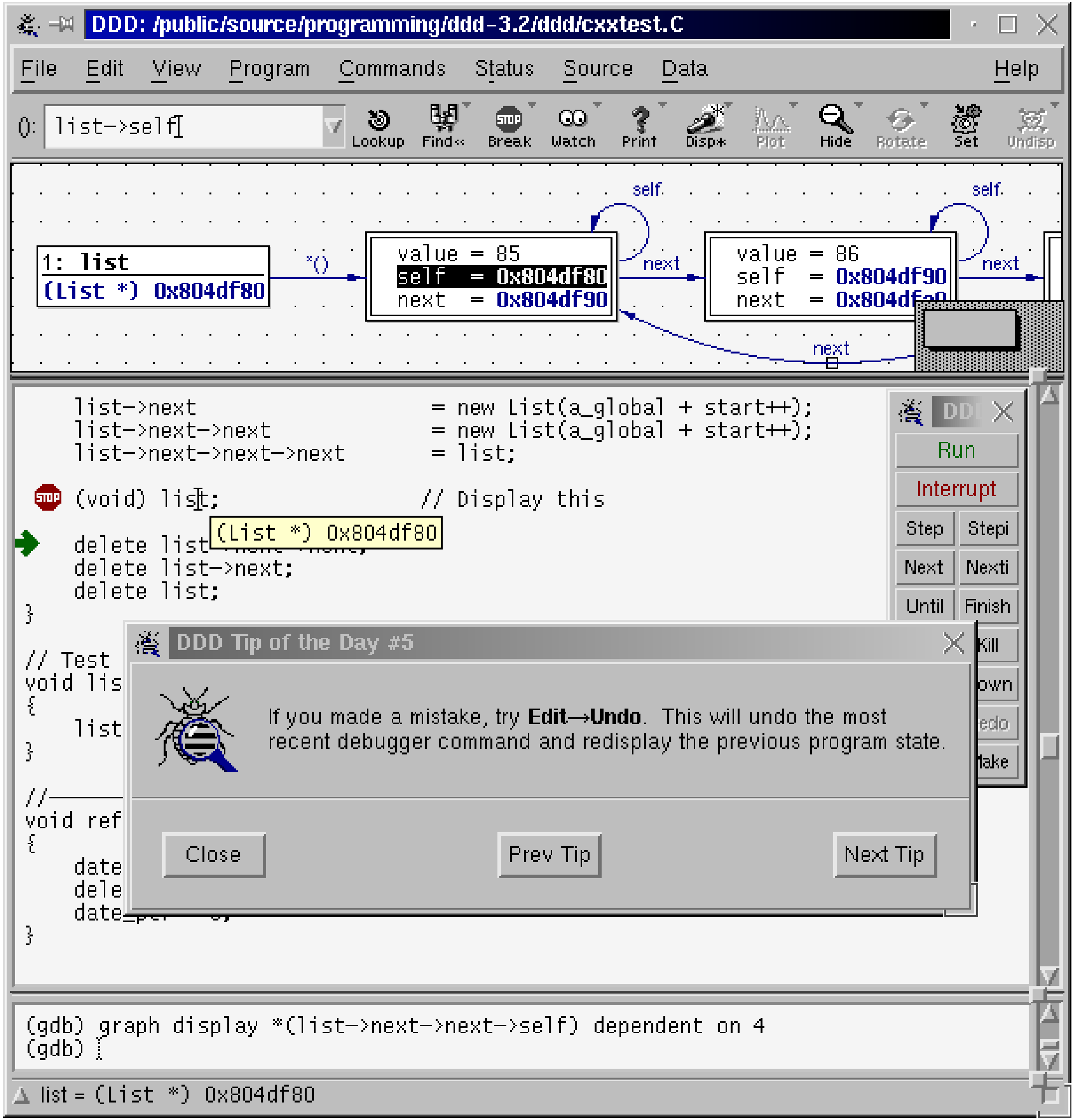
```
int main() {
        int some_var = 55;
        int array[10];
        int i;
        for (i=0;i<=10;i++)
                array[i] = i;
        printf("some_var = %d\n",
                some_var);
}
```

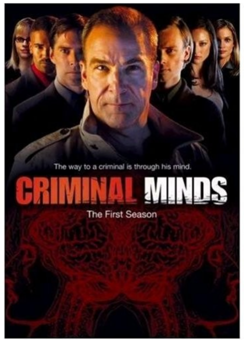
Sadly, valgrind won't help you here. Psych!

```
[weimer@weimer-laptop ~]$ ./a.out
some_var = 10
```

DDD

- Gnu Data Display Debugger
  - Similar in spirit to Visual Studio's built-in debugger
  - But for gdb, the Java debugger, the perl debugger, the python debugger, etc.
- How does this work? You tell me!





Profiling

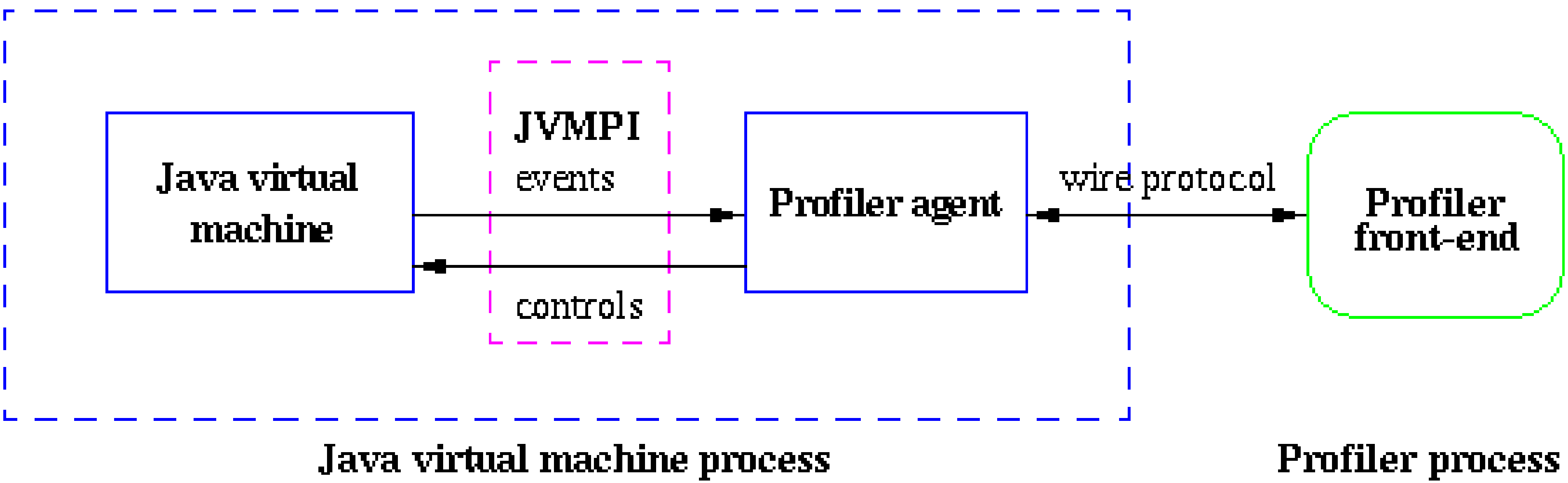
- A **profiler** is a performance analysis tool that measures the frequency and duration of function calls as a program runs.
- **Flat profile**
  - Computes the average call times for functions but does not break times down based on context
- **Call-Graph profile**
  - Computes call times for functions and also the call-chains involved

Event-Based Profiling

- Interpreted languages provide special hooks for profiling
  - Java: JVM-Profile Interface, JVM API
  - Python: sys.set_profile() module
  - Ruby: profile.rb, etc.
- You register a function that will get called whenever the target program calls a method, loads a class, allocates an object, etc.
  - You could do this for PA5: count the number of object allocations, etc.
  - (And we do some profiling for you in PA7.)

JVM Profiling Interface

- VM notifies profiler agent of various **events** (heap allocation, thread start, method invocation, etc.)
- Profiler agent issues control commands to the JVM and communicates with a GUI



Statistical Profiling

- You can arrange for the operating system to send you a **signal** (just like before) every X seconds (see **`alarm(2)`**)
- In the **signal handler** you determine the value of the target program counter
  - And append it to a growing list file
  - This is called **sampling**
- Later, you use that debug information table to map the PC values to procedure names
  - Sum up to get amount of time in each procedure

Sampling Analysis

- Advantages
  - Simple and cheap – the **instrumentation** is unlikely to disturb the program too much
  - No big slowdown
- Disadvantages
  - Can completely miss periodic behavior (e.g., you sample every k seconds but do a network send at times $0.5 + nk$ seconds)
  - High error rate: if a value is n times the sampling period, the expected error in it is sqrt(n) sampling periods
- Read the **`gprof`** paper for midterm2

While Derivation On The Board?

- If we have time, let's do this together ...
- E = $[\ x \to a\ ]$
- S = $[\ a \to 0\ ]$
- S' = $[\ a \to 1\ ]$

while x < 1 loop x <- x + 1 pool

Homework

- Midterm 2 – Mon April 21st In Class
  - Covers Lectures "Code Generation" to "Linking, Loading and Shared Libraries" (i.e., everything after Midterm 1) plus each WA and PA done during that time
  - Everything *after* Earley parsing
- Midterm 2 Review Session?
  - Post of the forum!