Profilers and Debuggers

Introductory Material

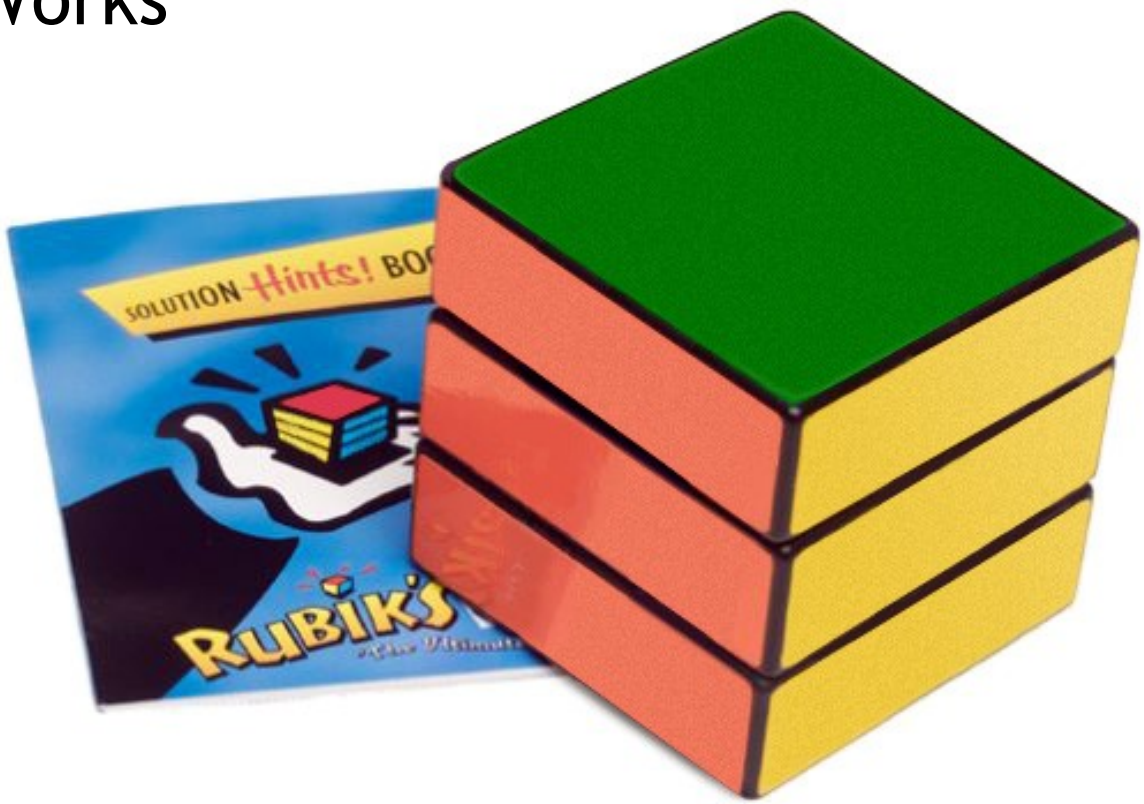
- First, who **doesn't** feel comfortable with assembly language?
  - This is a great opportunity to practice!
- Lecture Style:
  - "Sit on the table" and pose questions.
- Lecture Goal:
  - After the lecture you'll think, "Wow, that was all reasonable in retrospect. With a bit of time, I could have come up with those techniques."

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`**)
- Programs can use **signal handlers** – code that will be executed when the signal occurs.
  - Signal handlers are vulnerable to race conditions.

    (2+ threads access same variable, 1+ writes to it)

```c
#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);
}
```

Signal Example

- What might 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
  - system call = user program requests a service from the OS
  - Security: when can you debug process XYZ?
- 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 reakpoi

```
 .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"
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        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 program counter value = hardware breakpoint register value, signal an exception
  - Faster than software, works on embedded system 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: 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.

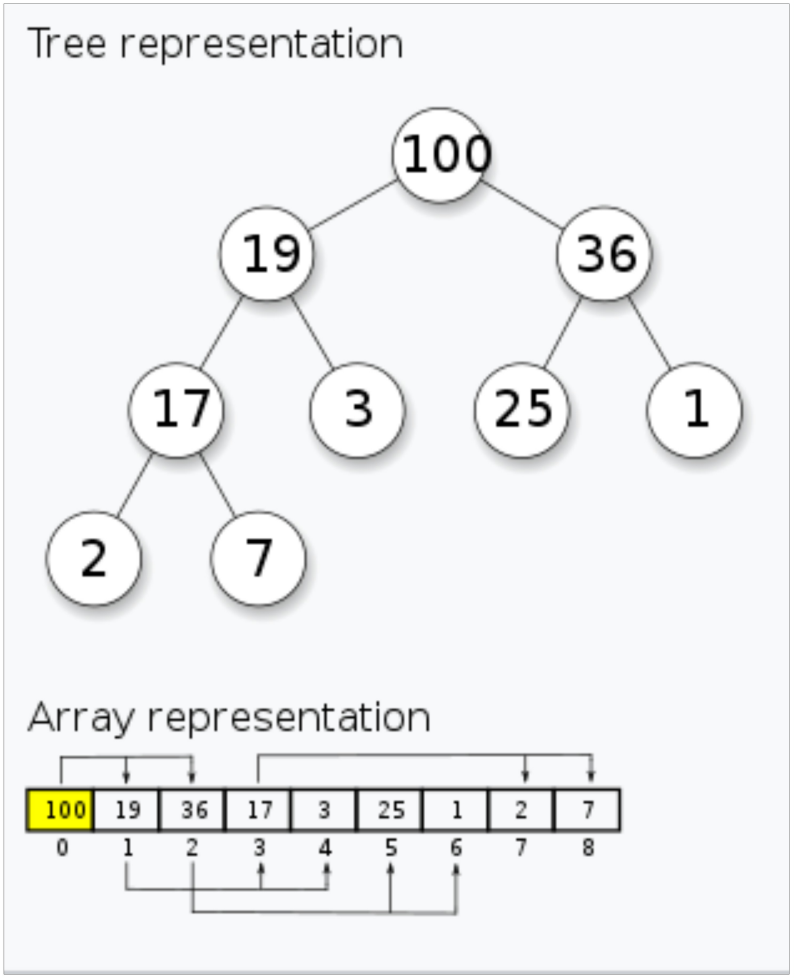
Social Media

- Name the social media platform most associated with memes about:
  - color vision of shrimp
  - Apollo's dodgeball
  - Goncharov
  - Spiders Georg

Data Structures

(student “memorial”)

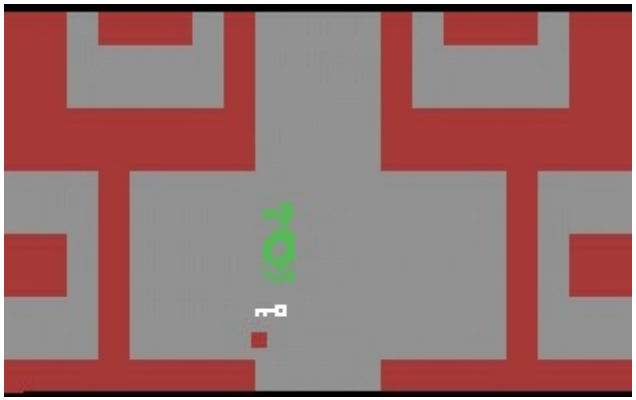
- *This* data structure can be viewed as an array or a tree. If node **A** is a parent of node **B** then the value at **A** is >= the value at **B**. In the binary version, the node **X** at position array[**X**] has parent array[**(X-1)/2**]. It is maximally efficient for implementing priority queues (and is relevant for Dijkstra's Algorithm).

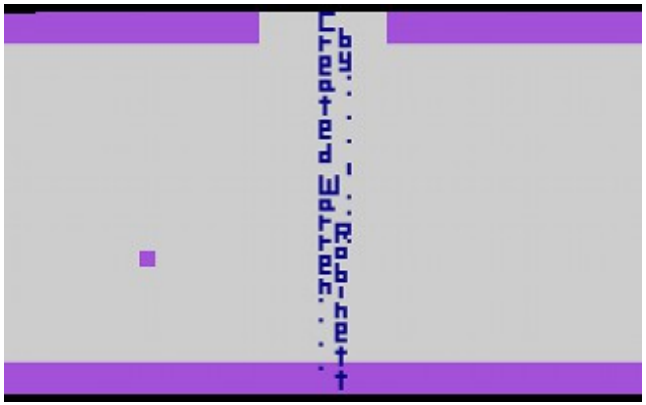


Video Game History

(student “memorial”)

- This 1979-1980 Atari 2600 video game introduced the first widely-known *Easter egg*. Atari did not allow game designers or programmers to credit themselves in any way (games were marketed and branded as produced by Atari overall). Warren Robinett included a secret room crediting himself as the designer. When a 15-year-old from Utah discovered it and wrote to Atari for an explanation, they tasked Brad Stewart with fixing it, but he said he would only change it to “Fixed by Brad Stewart”. Atari decided to leave it in game, dubbing such hidden features *Easter eggs* and saying they would include more in the future. The game itself involves carrying items around three castles to defeat three dragons.





Real-World Languages

- This Northern European language boasts 5.8 million speakers (including Linux author 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.
  - Example: Hyvää päivää!

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?

```
/* 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 x0 = 11 in
x = x + 22;                let x1 = x0 + 22 in
breakpoint ;       →       breakpoint ;
x = x + 33;                let x2 = x1 + 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, but also …

Time traveling debuggers [edit]

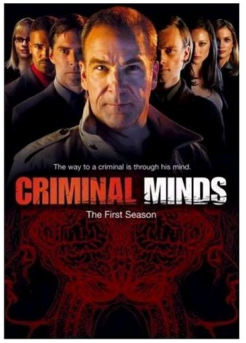
Examples of debuggers with the ability to step backwards:

Language	Debuggers
C++	rr for x86 Linux, Undo UDB for Linux[9]
R	provDebugR[10]
Python	PyTrace[11]
JavaScript	Wallaby.js,[12] Meiosis Tracer[13]
C#	RevDeBug
Java	RevDeBug for C# and Java,[14] WhyLine for Java,[15] Undo UDB
Elm	Elm Debugger, Elm Reactor[16]
OCaml	ocamldebug
Go	Undo UDB for Linux[17]
Rust	Undo UDB for Linux[18]
Windows Native	Microsoft Time Travel Debugging (TTD) Tool[19] for native Windows software eShard esReven Full System Timeless Analysis for Windows[21]
Linux Native	eShard esReven Full System Timeless Analysis for Linux[22]

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

Profiling



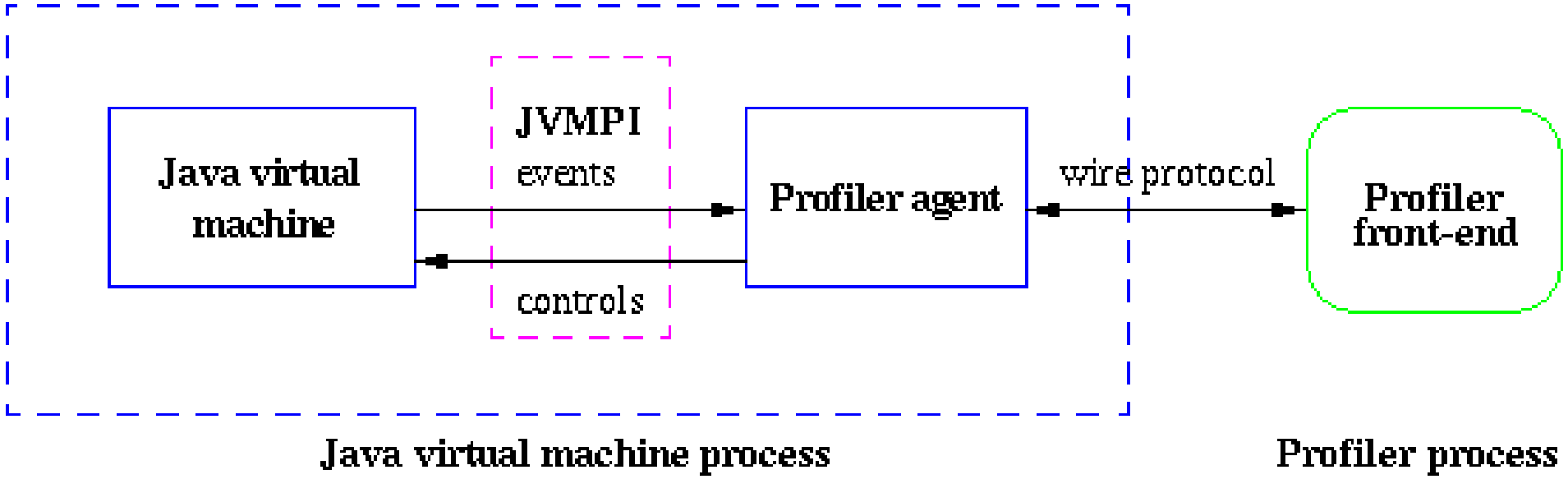
- A **profiler** is a performance analysis tool that measures the frequency and duration of function calls as a program runs.
- **Flat profile**
  - Computes the average call times for functions but does not break times down based on context
- **Call-Graph profile**
  - Computes call times for functions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

Event-Based Profiling

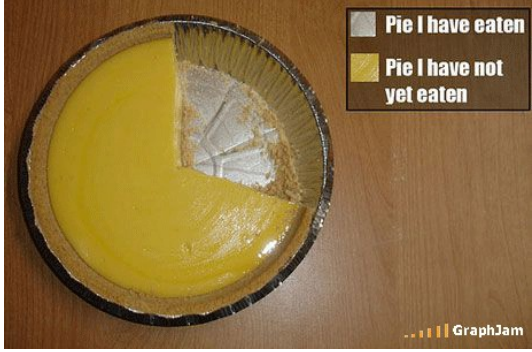
- Interpreted languages provide special hooks for profiling
  - Java: JVM-Profile Interface, JVM API
  - Python: sys.set_profile() module
  - Ruby: profile.rb, etc.
- You register a function that will get called whenever the target program calls a method, loads a class, allocates an object, etc.
  -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

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 + n*k* 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 → a]
- S = [a → 0]
- S' = [a → 1]

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

Homework

- Midterm 2 – End of Next Week
  - Covers Lectures "Code Generation" to "Language Security" (i.e., everything after Midterm 1) and PAs done during that time
  - Everything *after* parsing is in scope
  - Review sets and prior exams are available to help structure your studying
  - Format and logistics match Midterm 1