Introducing Parallel Computing in a Second CS Course

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Expose Students to PDC Concepts Early

P&D computing increasingly important

- P&D world (and students know it)
- Prepare work force, gradschool, undergraduate research

Want All CS majors see PDC concepts early and often

- Teach “Parallel Thinking” early
- Natural to think about P&D questions in different contexts later

Our Course: Introduction to Computer Systems (CS31)

CS in the Liberal Arts: Fewer Courses & Shallow Prereq Hierarchy

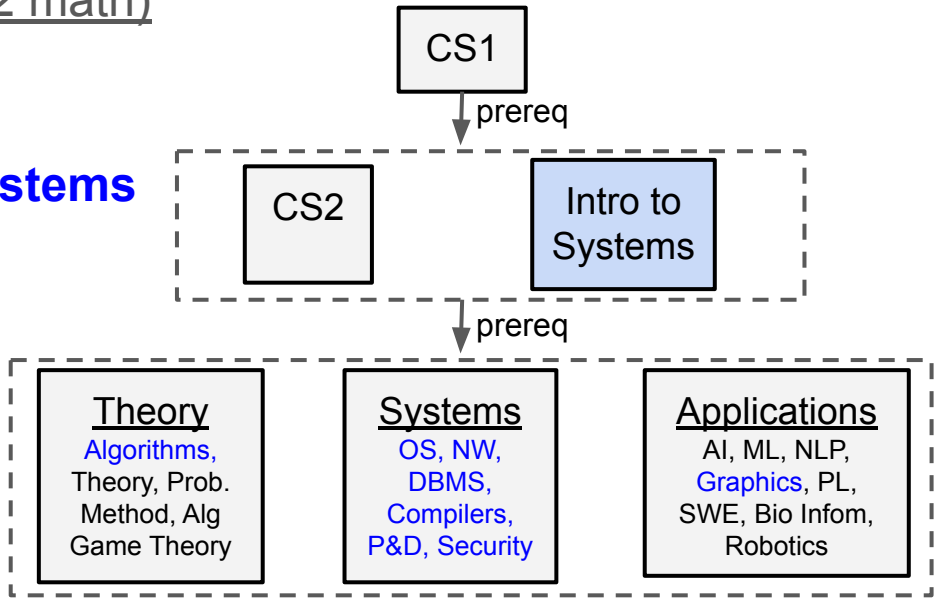
Swarthmore: 8 CS courses in major (+ 2 math)

1 Introductory-level: CS1

2 Intermediate-level: CS2 & **Intro to Systems**

5 Upper-level:

- Grouped in 3 buckets
- At least 1 in each for breadth
- P&D in all Systems, some other



Why PDC in a Second Course?

- Early Curricular Exposure to PDC
  - Provides common background of introduction to systems and PDC topics to every student in any upper-level course
  - Increased Depth vs. in CS1: Can focus more on PDC and less on basic algorithmic problem solving & intro programming
  - Increased Breadth at intro level vs. upper-level: introduce many concepts will see again in different contexts

- Easier Part of our Curriculum to Change to incorporate PDC topics
  - Replaced more traditional Computer Organization course
  - More constraints/goals/opinions about CS1 and CS2 (Data structures & Algs)

CS31 Introduces Many TCPP Topics

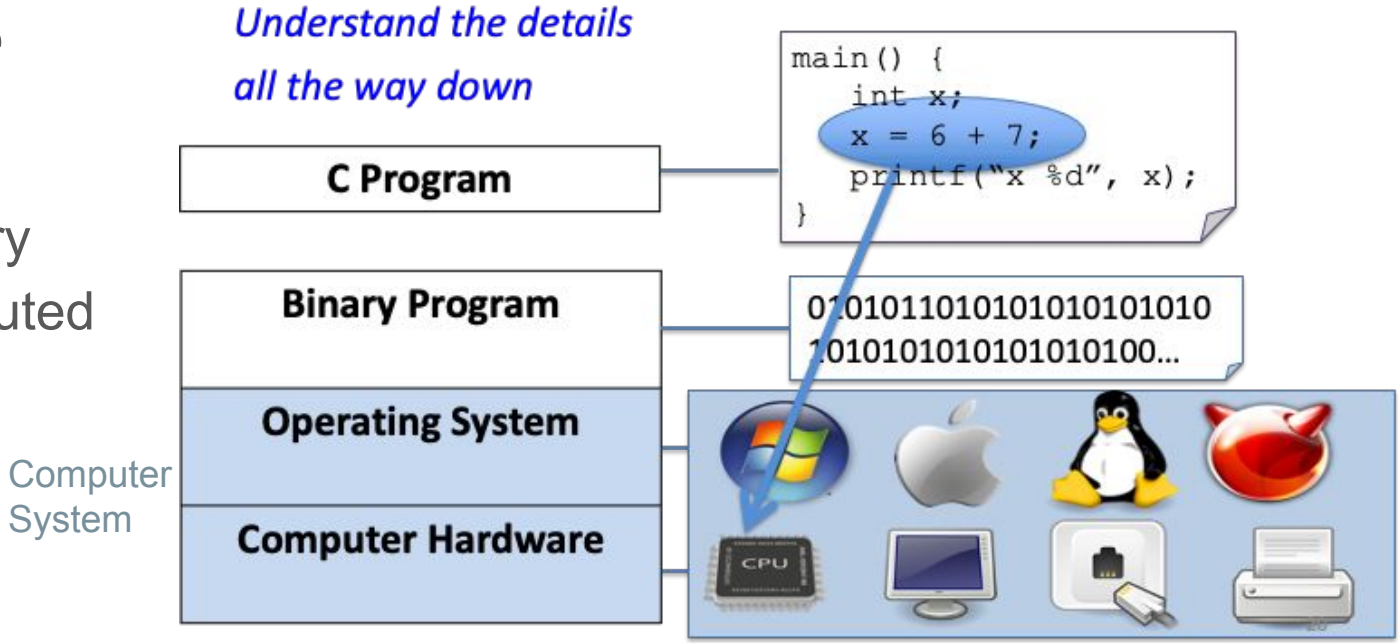
TCPP Category	Intro to Systems Topics
Pervasive	concurrency, asynchrony, locality, performance
Architecture	multicore, caching, latency, bandwidth, atomicity, consistency, coherency, pipelining, instruction execution, memory hierarchy, multithreading, buses, process ID, interrupts
Programming	shared memory parallelization, pthreads, critical sections, producer-consumer, synchronization, deadlock, race cond, memory data layout, locality, signals
Algorithms	dependencies, space/memory, speedup, Amdahl's law, synchronization, efficiency

(Table 1)

Course Goal 1: How a Computer Runs a Program

A vertical slice through the computer

from HLL to binary instructions executed by HW circuitry

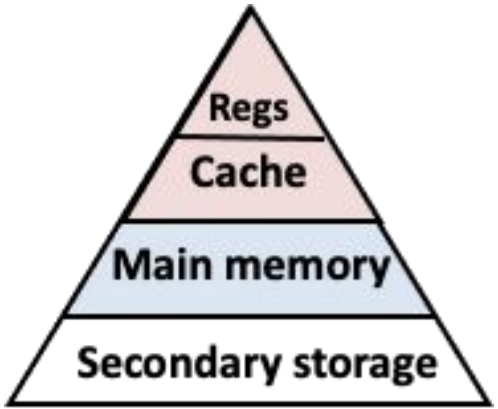


Course Goal 2: Systems Costs and Efficiency

It is not all big-O

Recognize & Evaluate systems costs associated with running a program

- Focus on Memory Hierarchy & caching
- Also in context of OS and parallel

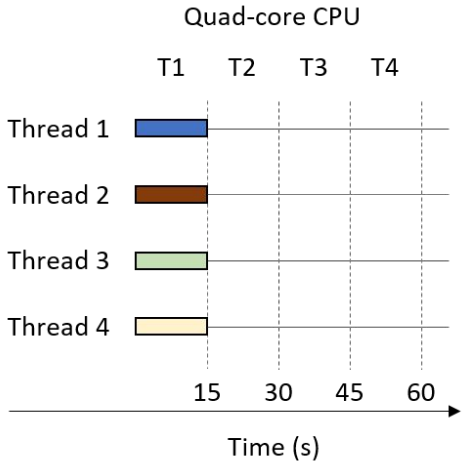


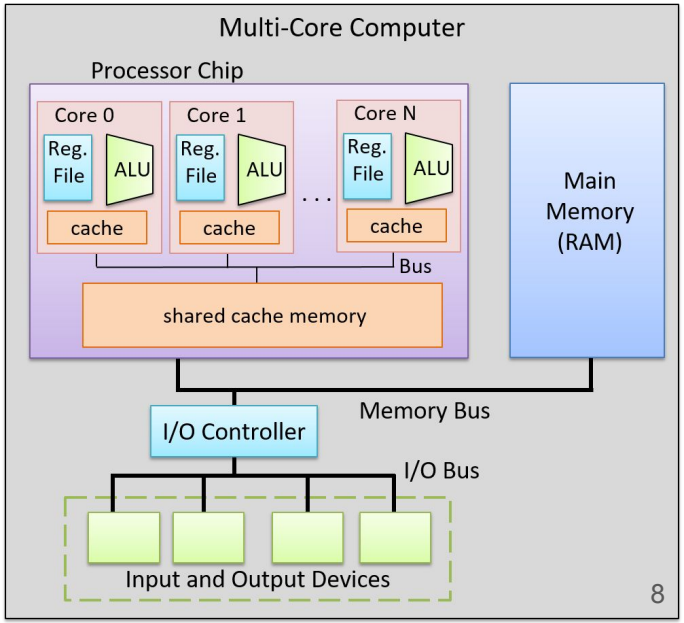
Course Goal 3: Intro to Parallel Computing

Taking advantage of the power of parallel computing

In the context of goals 1 and 2: how programs run & efficiency

- Focus on Shared Memory parallelism
- Multicore and pthreads
- Synchronization



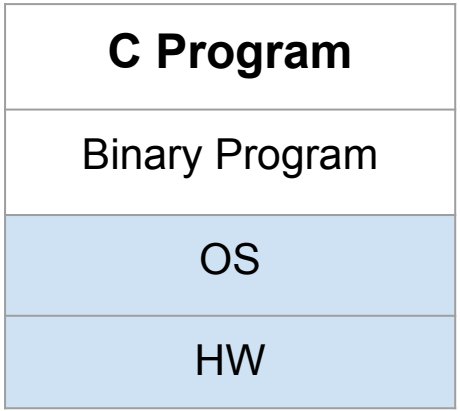


Class Structure

- Lecture: typically 60 students (large for LACS)
  - Lecture with active learning: clicker questions, group discussion, reading quiz
- Weekly Lab Session (90 minutes per week)
  - Learn tools for doing lab work: C, gdb, valgrind, logisim, pthreads
- Lab Assignments
  - C, assembly, and pthreads programming, logisim, gdb assembly tracing
- Weekly Written Homeworks
  - Short, reinforce lecture topics, have used assigned HW-groups
- Course-Specific Student Mentors (CS Ninjas, SIGCSE'14)
  - Help in Lab sessions, in-class activities, Run evening help sessions for lab work

C Programming: used throughout the course

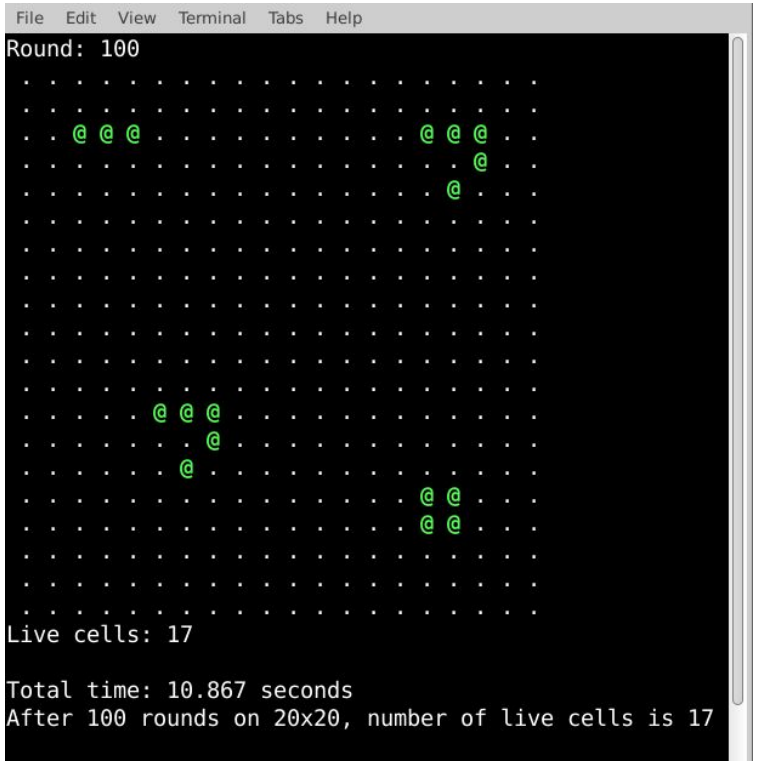
- 1 week intro to C
  - Students have a CS1 background in Python (or Java)
- New features introduced in context of other topics
  - Pointers
  - Dynamic memory allocation
  - 2D arrays, structs



Part of a Vertical Slice through a Computer (Goal 1)

C Programming: Labs and HWs

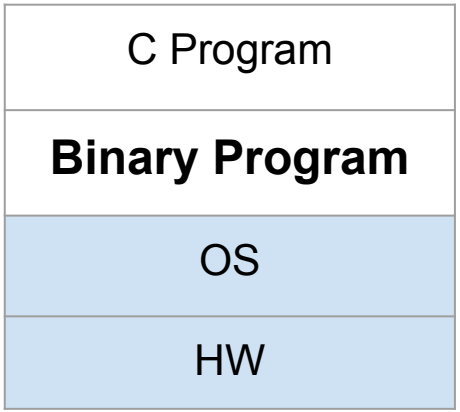
- Learning C Labs
  - Intro: 1D static arrays, searching, sorting
  - 1D dynamic arrays, searching, sorting
  - 2D dynamic arrays, GOL w/ASCII & ParaVis visualization (EduPar'19)



- HW: stack drawing, code tracing, expressions & type

Binary Representation

- Usually 1st topic, before intro C
- Topics
  - C types in binary: unsigned and signed (2's complement)
  - Binary arithmetic (+, -) signed unsigned, overflow
  - Bitwise operations



Part of how program encoded to run on computer
And how arithmetic on binary values works
(Goal 1)

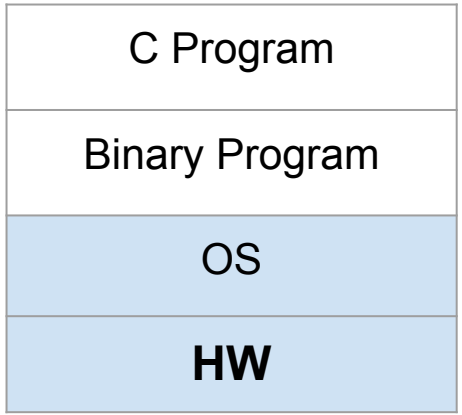
Binary Representation Labs and HW

- Simple C program to evaluate answers to questions about binary representation and arithmetic
  - First C program: introduces compilation, basic syntax, simple functions
- Written part: convert decimal/binary/hex, binary arithmetic

```
   11111111 (-1)        10101100        0xff  → 0b11111111 -> 255
+  00000001  (1)      & 11010111
   --------             --------        0xff  → 0b11111111 -> -1
 1 00000000  (0)        10000100
carry out                                                    …
```

Architecture: focus on CPU architecture

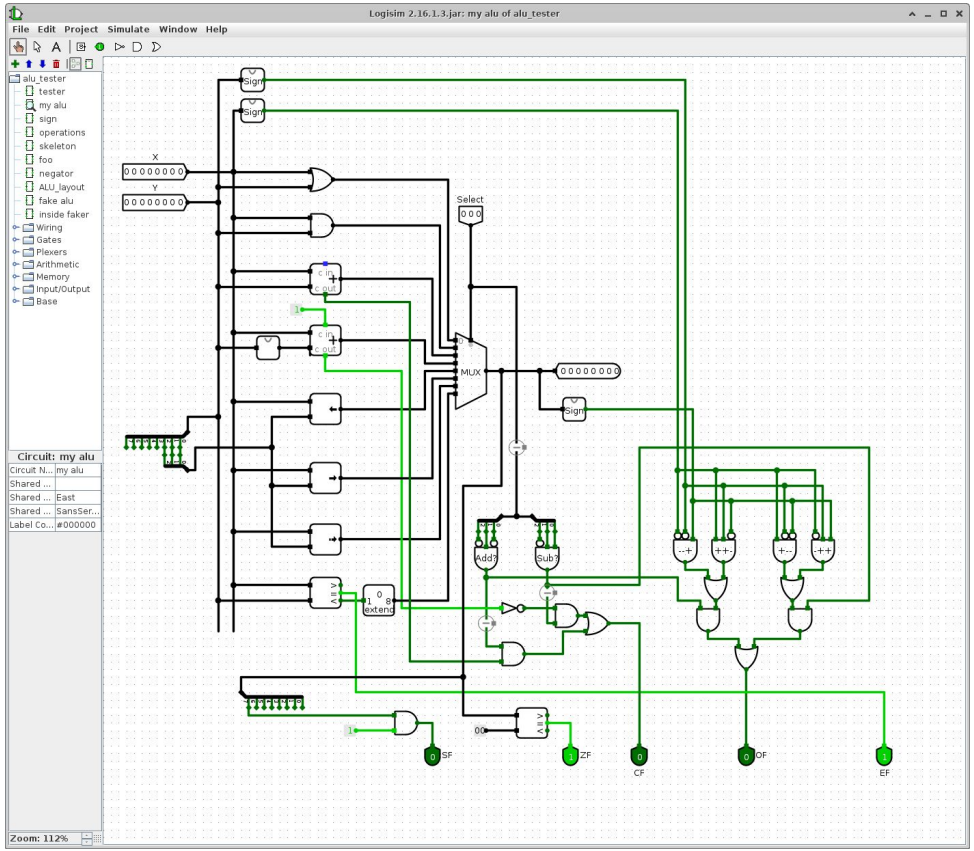
- Von Neumann Architecture
- ISA
- Simple circuits from basic gates (AND, OR, NOT)
- Arithmetic-logic, Storage, Control
- ALU, Register File, Clock
- Instruction Execution, Pipelining
- Some Modern Architectures (**multicore**, multithreaded,ILP)
- Theme of Abstraction as add complexity (from gates to CPU)



How HW is designed to execute a stream of binary instructions on binary data (Goal 1)

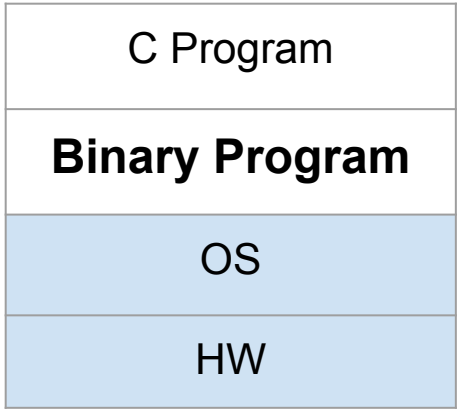
Architecture Labs and HWs

- Labs using Logisim
  - 4-bit adder from AND, OR, NOT gates
  - Build CPU for 8 instruction ISA (ALU, Regs, IR, clock) w/condition codes
- Truth table to/from circuit
- Circuit Tracing



Assembly Programming

- Translating C to/from Assembly
- X86 (ARM-64 in Fall'22)
  - ISA: instruction set, registers
  - Arithmetic/logic
  - Control, Loops
  - Functions, the Stack
  - Pointers
  - Array & Struct layout & access



Part of how program encoded to run on computer (Goal 1)

Tie to C code and to what know about how CPU designed to run program instructions

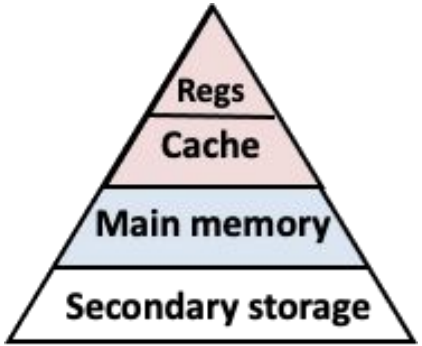
Assembly Programming Labs and HWs

- Translating between C & Assembly
  - simple instructions
  - loops, if-else
  - functions
  - arrays and pointers
- Binary Maze Program
  - gdb to find way out
  - based on Bryant & O'Hallaron's Binary Bomb
- Code tracing showing stack & register contents

```
   0x00001a38 <+73>:    mov    (%ebx),%eax
   0x00001a3a <+75>:    add    %eax,%eax
   0x00001a3c <+77>:    cmp    %eax,0x4(%ebx)
   0x00001a3f <+80>:    je     0x1a31 <phase_2+66>
   0x00001a41 <+82>:    sub    $0xc,%esp
   0x00001a44 <+85>:    push   $0x2
   0x00001a46 <+87>:    call   0x237b <tripped_up>
   0x00001a4b <+92>:    add    $0x10,%esp
   0x00001a4e <+95>:    jmp    0x1a31 <phase_2+66>
   0x00001a50 <+97>:    mov    0x1c(%esp),%eax
   0x00001a54 <+101>:   xor    %gs:0x14,%eax
   0x00001a5b <+108>:   jne    0x1a63 <phase_2+116>
   0x00001a5d <+110>:   add    $0x24,%esp
   0x00001a60 <+113>:   pop    %ebx
   0x00001a61 <+114>:   pop    %esi
   0x00001a62 <+115>:   ret
   0x00001a63 <+116>:   call   0x1a64 <phase_2+117>
End of assembler dump.
(gdb) break *0x00001a38
Breakpoint 1 at 0x1a38
(gdb) ni
```

Memory Hierarchy and Caching

- Memory Hierarchy
  - buses, devices
  - W/R mechanics
- CPU Caching
  - Direct Mapped, Set Associative
  - Locality
  - Data layout, access patterns
- Written HW
  - Address Translation
  - DM & SA Cache effects on sequence of W/R

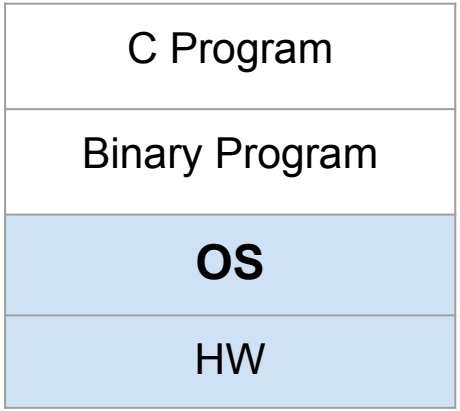


C Program
Binary Program
OS
HW

How Computer System Designed to Efficiently Run programs and Systems Costs with program execution (Goal 2)

Introduction to Operating Systems

- Role of OS & how works: booting, interrupts, kernel/user mode
- Two main Abstractions Related to How Computer Runs Program
  1. **Processes**: state, context switch, multiprogramming/timesharing, process hierarchy, fork, exec, wait, exit, signals, asynchrony, concurrency
  2. **VM**: VAS, VA/PA, paging, replacement, TLB



Part of how program is run on a computer (Goal 1)

Part of how to efficiently run program on computer and systems costs assoc with running program (Goal 2)

Operating System Labs & HWs

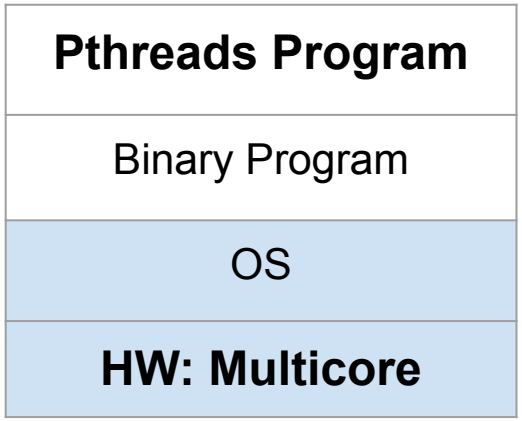
- Unix shell & parse command library:
  - foreground, background (asynch, signals), history
  - starting point for lab in UL OS
- Process HW: tracing code with fork/exec/wait/, concurrency
- VM: page table translations, replacement

```
tiascs31shell> sleeper &
tiascs31shell> ps
    PID TTY          TIME CMD
1248792 pts/0    00:00:00 tcsh
1249679 pts/0    00:00:00 cs31shell
1249703 pts/0    00:00:00 sleeper
1249705 pts/0    00:00:00 ps
tiascs31shell> history
     0  ls
     1  sleeper &
     2  ps
     3  history
tiascs31shell> !1
tiascs31shell> history
     0  ls
     1  sleeper &
     2  ps
     3  history
     4  sleeper &
     5  history
tiascs31shell> ps
    PID TTY          TIME CMD
1248792 pts/0    00:00:00 tcsh
1249679 pts/0    00:00:00 cs31shell
1249736 pts/0    00:00:00 sleeper
1249749 pts/0    00:00:00 ps
tiascs31shell>
```

Parallel Computing

- Focus on Shared Memory
  - Already seen Multicore
  - Parallelism vs. Concurrency

- OS's Thread Abstraction:
  - Follows from Process and VM
  - Thread Scheduling
  - VAS Sharing



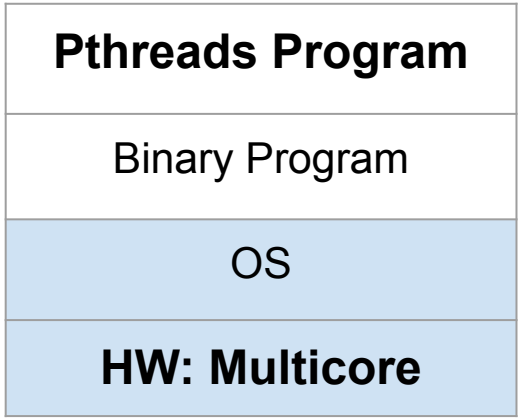
Part of how a parallel program is run on a computer (goal 1)

Part of how to efficiently write program to run on multicore computer (goal 2)

Parallel Computing (cont.)

- Parallel Pthreads Programming
  - Thread create-join
  - Synchronization, mutual exclusion, critical sections
  - mutex, barrier, condition vars
  - Race condition, deadlock

- Speed-up, Amdahl's law
  - Parallel Costs/Overheads
  - Embarrassingly Parallel
  - Superlinear (tie to mem hier)

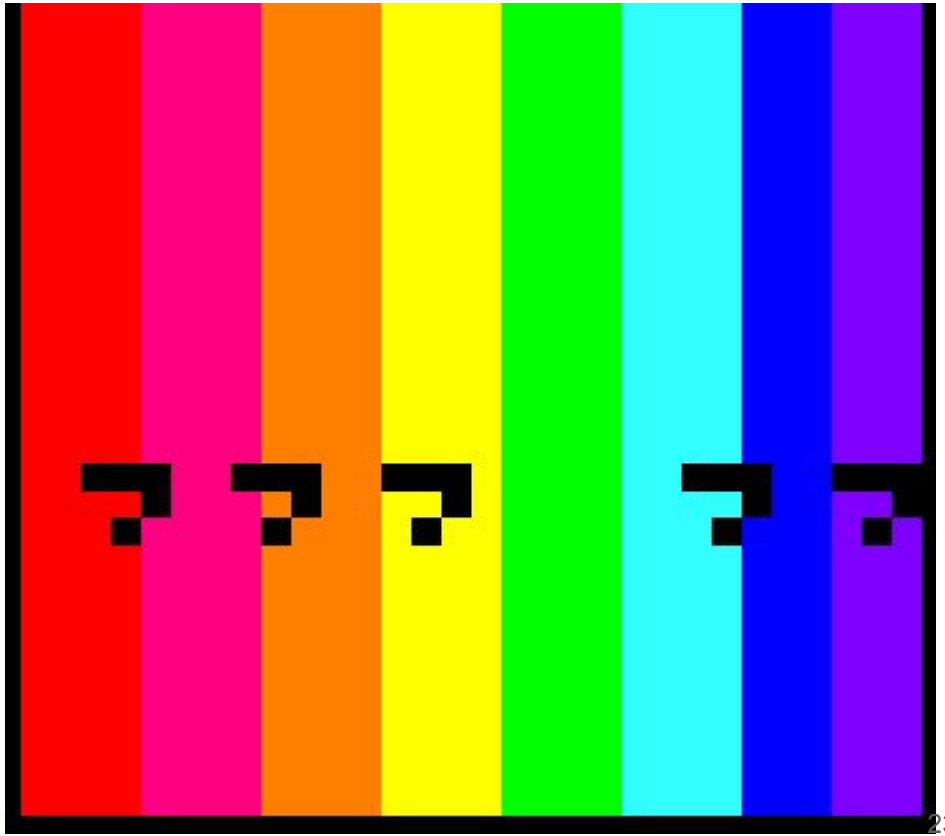


Part of how a parallel program is run on a computer (goal 1)

Part of how to efficiently write program to run on multicore computer (goal 2)

Parallel Computing Labs and HWs

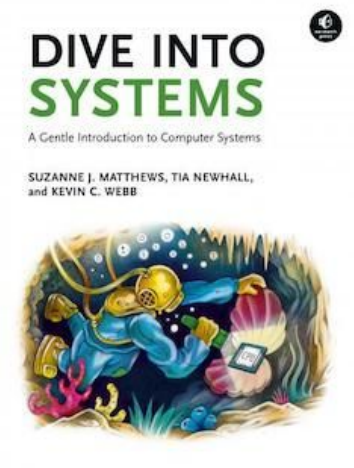
- Written synchronization, parallel execution
- Producer/Consumer bounded buffer
- Pthreads GOL w/ASCII & ParaVis (EduPar'19)
  - Vary partitioning & number threads
  - ParaVis helps debug column/row partitioning
  - Starting point for lab in UL P&D Computing



Issue: finding the right textbook

Problem:

- Needed introductory-level coverage of a broad set of organization, systems, parallel topics



Solution: write one (Matthews, Newhall, Webb)

- Free, online textbook diveintosystems.org
- Broad set of topics at Intro level
- Useful to a range of courses/uses (30+ institutions)
- SIGCSE'21 early adopter evaluation paper
- New NSF funded effort to add interactive exercises
- Print version out by fall (will always remain free online)

CS31 Student Survey Results (~300 students in 5 recent offerings)

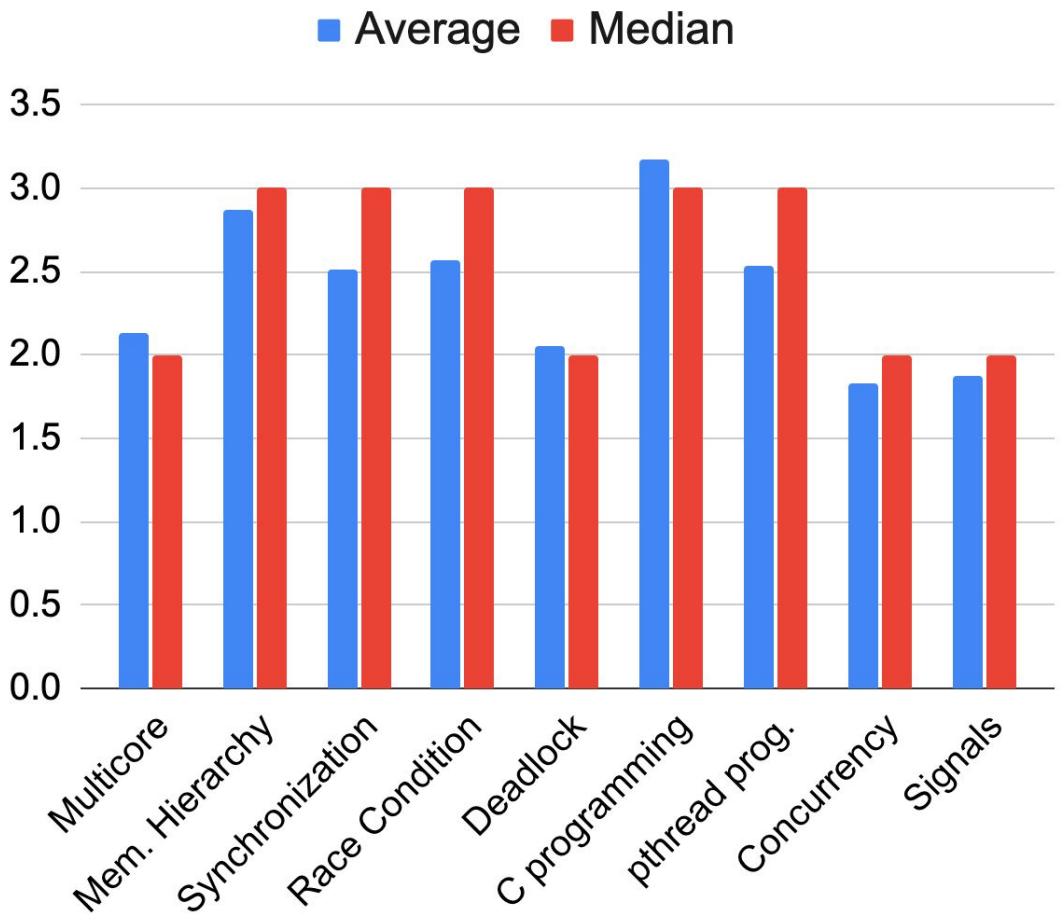
- Appreciated Exposure to PDC
  - *“Parallelism is great! Also pipelining. Those two concepts are super applicable to life broadly”*
  - *“exposed to a great deal of new concepts, especially…new ways for managing programs like threading and forking”*
- Gained new Systems Perspective, evaluating trade-offs
  - “I like how we unpacked a lot of what goes on behind the scenes”
  - “really interesting to think about…questions of efficiency in different things we talked about, and see how those really apply to computer systems that we use every day”
  - “should keep in mind both Big O and what happens in hardware”
- Built Confidence in thinking about systems & parallelism
  - “I can’t wait to take more systems courses!”
  - “learning how to parallelize programs were really interesting, and now I want to take parallel and distributed computing”

Upper-level Student's Understanding of PDC Concepts from CS31

Bloom's Taxonomy Rantings

- 0: don't know
- 1: recognize
- 2: can define
- 3: can explain
- 4: can apply

Don't expect level 4 understanding on all topics after CS31 (intro level, 1st introduction)



Conclusions

- A second course introducing PDC works well in our curriculum, and we believe more generally too (10+ years of CS31 at Swarthmore)
  - Students with CS1 background ⇒ can focus more on PDC
  - CS31 prerequisite to upper-level courses ensures all students see PDC early
- Focus on Shared Memory Parallelism
  - Fits naturally with larger course goals, follows naturally from previous course topics
  - Allows for more depth of coverage
- Faculty teaching Upper-level courses with PDC content note w/CS31:
  - Students naturally think in parallel and distributed ways from day one
  - Students start with programming and thinking skills and PDC background that allows us to spend more time on advanced PDC in upper-level courses (can cover more PDC and cover more in-depth than before)

Thank you.

Questions?

CS31 Webpages with resources: www.cs.swarthmore.edu/~newhall/cs31

Dive into Systems Textbook: diveintosystems.org/