CONCURRENCY: INTRODUCTION

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ADMINISTRIVIA

- Project 4 is out. Due March 6th
- Project 2 grades very soon

- Midterm 1 details: Piazza, Canvas

AGENDA / LEARNING OUTCOMES

- Virtual memory: Summary
- Concurrency
  - What is the motivation for concurrent execution?
  - What are some of the challenges?

RECAP

SWAPPING

OS goal: Support processes when not enough physical memory

- Single process with very large address space
- Multiple processes with combined address spaces

User code should be independent of amount of physical memory

- Correctness, if not performance

CLOCK ALGORITHM

Hardware

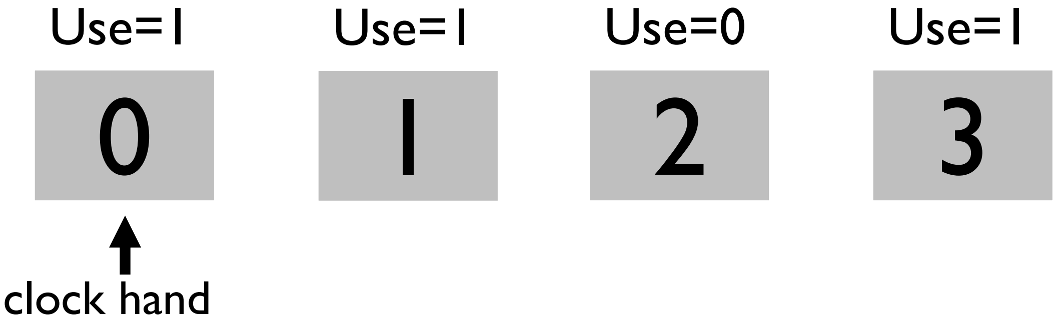
- Keep use (or reference) bit for each page frame
- When page is referenced: set use bit

Operating System

- Page Replacement:
  - Keep pointer to last examined page frame
  - Traverse pages in circular buffer
  - Clear use bits as we search
  - Stop when find page with already cleared use bit, replace this page

CLOCK: LOOK FOR A PAGE

Physical Mem:



→ Evict page 2 (not recently used).
Bring in page 4

Clarification:
Use bit for page 4?

Clarification:
Where does the hand start from next?

https://courses.cs.washington.edu/courses/csep544/99au/minirel/bufmgr.html

CLOCK EXTENSIONS

Replace multiple pages at once

- Intuition: Expensive to run replacement algorithm and to write single block to disk
- Find multiple victims each time and track free list

Use dirty bit to give preference to dirty pages

- Intuition: More expensive to replace dirty pages
  Dirty pages must be written to disk, clean pages do not
- Replace pages that have use bit and dirty bit cleared

GLOBAL VS LOCAL REPLACEMENT

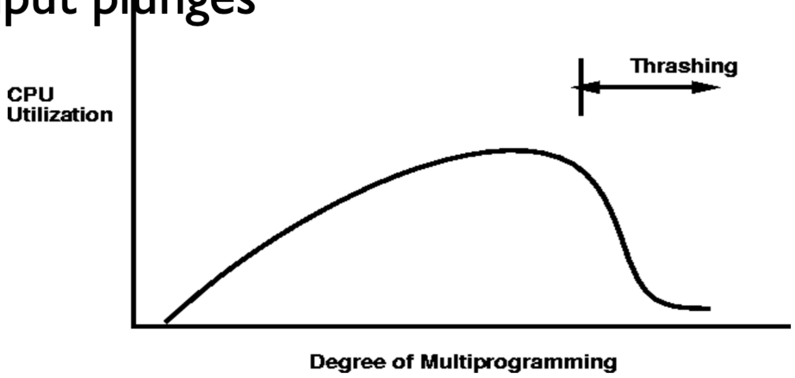
What if a victim page belongs to another process?

- Fixed space algorithms
  - each process is given a limit of pages it can use
  - when it reaches its limit, it replaces from its own pages
  - local replacement: some process may do well, others suffer
- Variable space algorithms
  - processes' set of pages grows and shrinks dynamically
  - global replacement: one process can ruin it for the rest
  - Clock is global replacement

THRASHING

- As page fault rate goes up, processes get suspended on page out queues for the disk
- System may try to optimize performance by starting new jobs
- Starting new jobs will reduce the number of page frames available to each process, increasing the page fault requests
- System throughput plunges

Solution? Stop running some processes



SUMMARY: VIRTUAL MEMORY

Abstraction: Virtual address space with code, heap, stack

Address translation

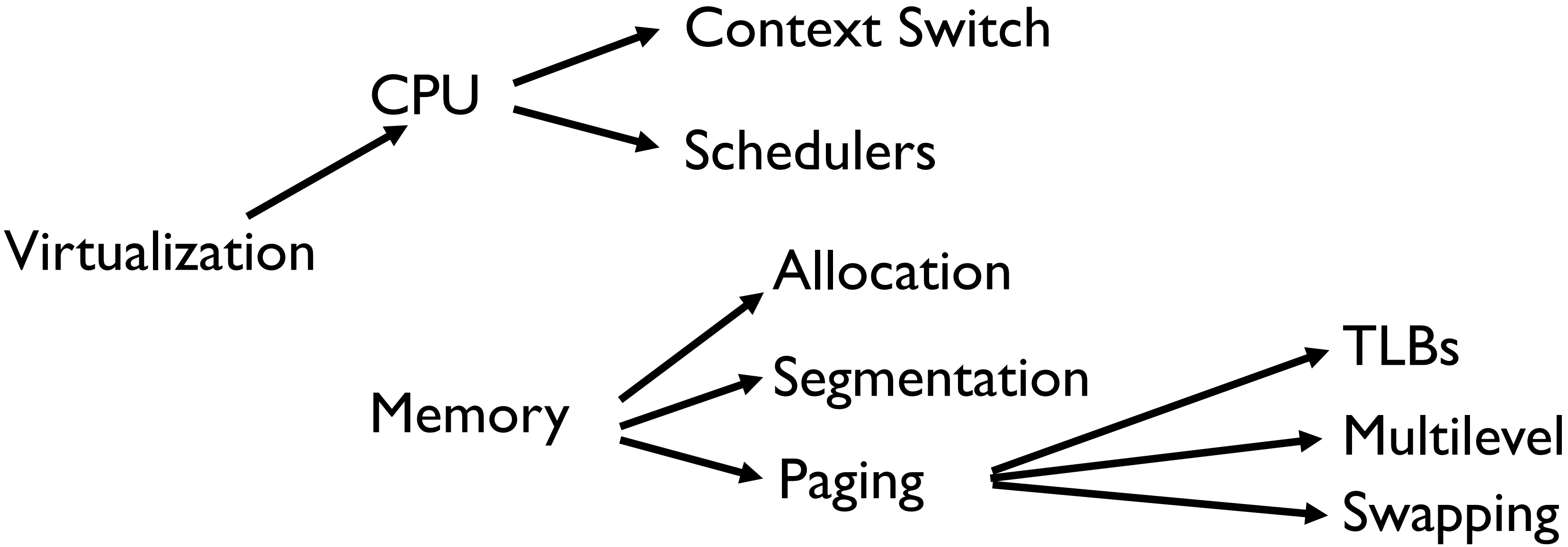
- Contiguous memory: base, bounds, segmentation
- Using fixed sizes pages with page tables

Challenges with paging

- Extra memory references: avoid with TLB
- Page table size: avoid with multi-level paging, inverted page tables etc.

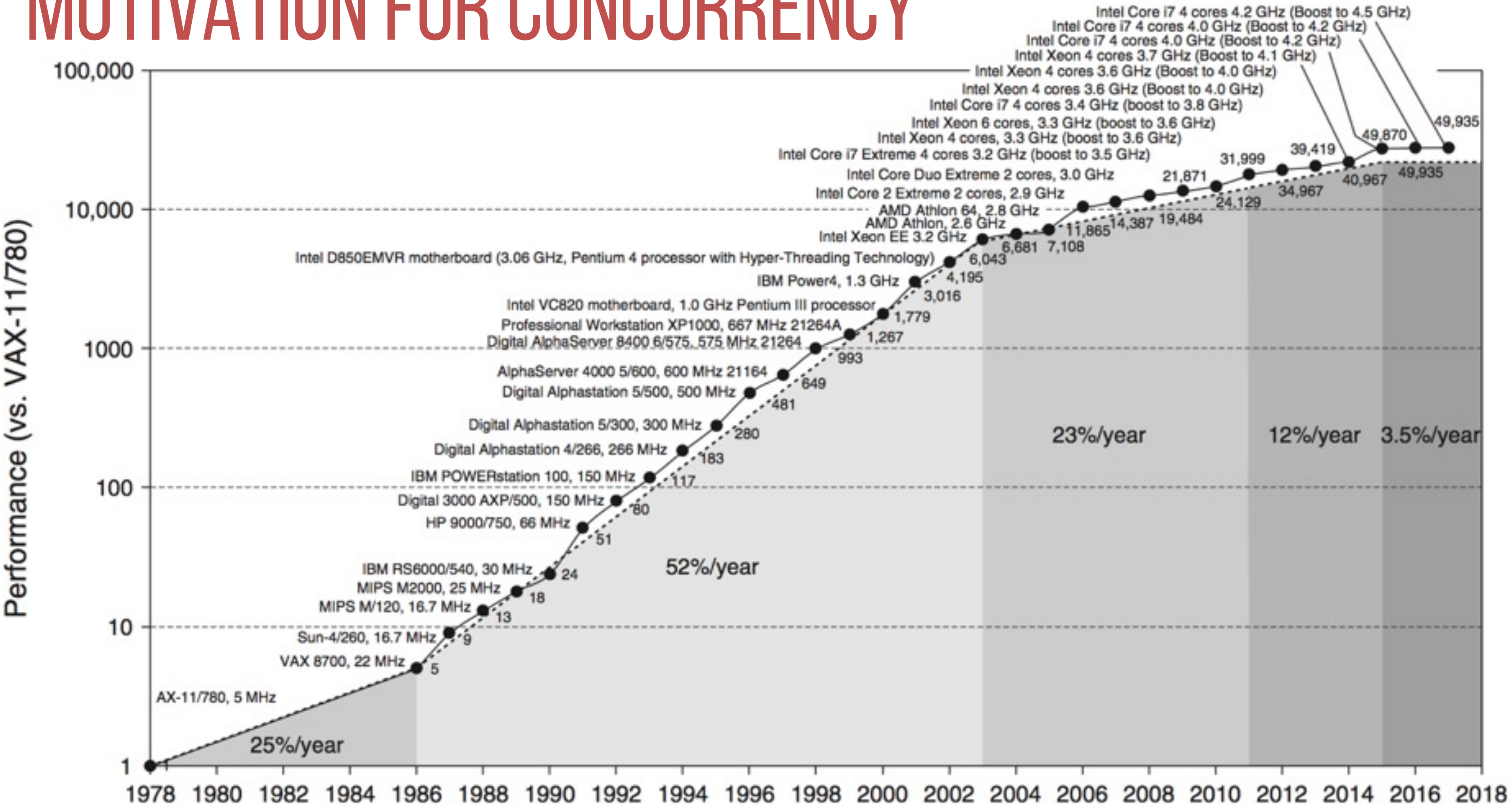
Larger address spaces: Swapping mechanisms, policies (LRU, Clock)

REVIEW: EASY PIECE 1



CONCURRENCY

MOTIVATION FOR CONCURRENCY



MOTIVATION

CPU Trend: Same speed, but multiple cores

Goal: Write applications that fully utilize many cores

Option 1: Build apps from many communicating **processes**

- Example: Chrome (process per tab)
- Communicate via pipe() or similar

Pros?

- Don't need new abstractions; good for security

Cons?

- Cumbersome programming
- High communication overheads
- Expensive context switching (why expensive?)

CONCURRENCY: OPTION 2

New abstraction: thread

Threads are like processes, except:

multiple threads of same process share an address space

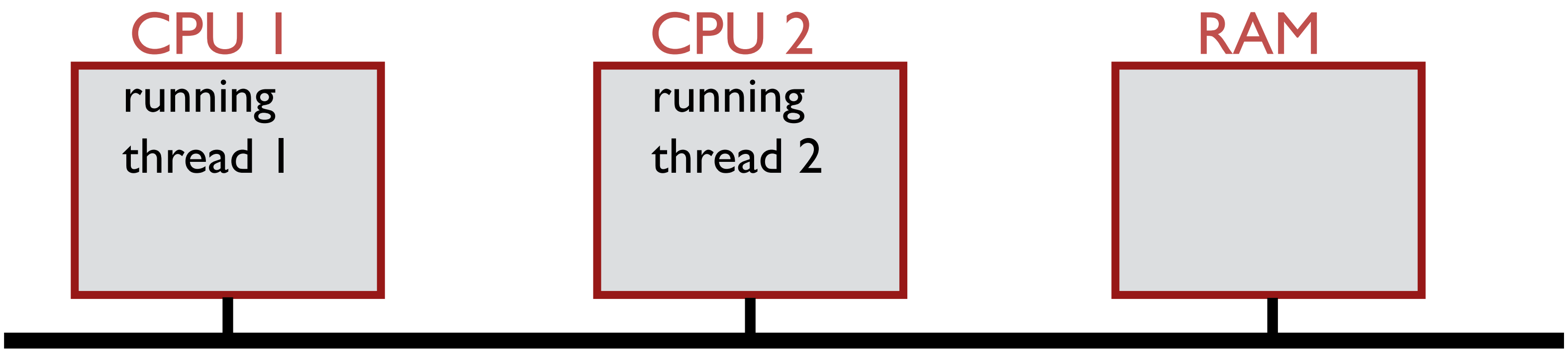
Divide large task across several cooperative threads

Communicate through shared address space

COMMON PROGRAMMING MODELS

Multi-threaded programs tend to be structured as:

- **Producer/consumer**
  Multiple producer threads create data (or work) that is handled by one of the multiple consumer threads
- **Pipeline**
  Task is divided into series of subtasks, each of which is handled in series by a different thread
- **Defer work with background thread**
  One thread performs non-critical work in the background (when CPU idle)



What state do threads share?

THREAD VS. PROCESS

Multiple threads within a single process share:

- Process ID (PID)
- Address space: Code (instructions), Most data (heap)
- Open file descriptors
- Current working directory
- User and group id

Each thread has its own

- Thread ID (TID)
- Set of registers, including Program counter and Stack pointer
- Stack for local variables and return addresses
  (in same address space)

OS SUPPORT: APPROACH 1

User-level threads: Many-to-one thread mapping

- Implemented by user-level runtime libraries

  Create, schedule, synchronize threads at user-level

- OS is not aware of user-level threads

  OS thinks each process contains only a single thread of control

Advantages

- Does not require OS support; Portable
- Lower overhead thread operations since no system call

Disadvantages?

- Cannot leverage multiprocessors
- Entire process blocks when one thread blocks

OS SUPPORT: APPROACH 2

Kernel-level threads: One-to-one thread mapping

- OS provides each user-level thread with a kernel thread
- Each kernel thread scheduled independently
- Thread operations (creation, scheduling, synchronization) performed by OS

Advantages

- Each kernel-level thread can run in parallel on a multiprocessor
- When one thread blocks, other threads from process can be scheduled

Disadvantages

- Higher overhead for thread operations
- OS must scale well with increasing number of threads

THREAD SCHEDULE

```
volatile int balance = 0;
int loops;

void *worker(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
      balance++;
    }
    pthread_exit(NULL);
}
```

```
int main(int argc, char *argv[]) {
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", balance);
    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", balance);
    return 0;
}
```

» ./threads 100000

Initial value : 0

Final value   : 162901

THREAD SCHEDULE #1

```
balance = balance + 1;
balance at 0x9000
```

State:

```
0x9000: 100
%eax:
%rip = 0x195

0x195  mov 0x9000, %eax
0x19a  add $0x1, %eax
0x19d  mov %eax, 0x9000
```

thread control blocks:

Thread 1	Thread 2
%eax: %rip:	%eax: %rip:

THREAD SCHEDULE #2

```
balance = balance + 1;
balance at 0x9cd4
```

State:

```
0x9000: 100
%eax:
%rip = 0x195

0x195   mov 0x9000, %eax
0x19a   add $0x1, %eax
0x19d   mov %eax, 0x9000
```

thread control blocks:

Thread 1	Thread 2
%eax:	%eax:
%rip:	%rip:

TIMELINE VIEW

Thread 1

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

mov %eax, 0x123

QUIZ 14

https://tinyurl.com/cs537-sp23-quiz14

Process A with threads TA1 and TA2 and process B with a thread TB1.

1. With respect to TA1 and TA2 which of the following are true?

2. Which of the following are true with respect to TA1 and TB1?

Thread 1	Thread 2
mov 0x123, %eax	
add %0x1, %eax	
	mov 0x123, %eax
mov %eax, 0x123	
	add %0x2, %eax
	mov %eax, 0x123

Thread 1	Thread 2
	mov 0x123, %eax
	add %0x2, %eax
	mov %eax, 0x123
mov 0x123, %eax	
add %0x1, %eax	
mov %eax, 0x123	

Thread 1	Thread 2
	mov 0x123, %eax
mov 0x123, %eax	
	add %0x2, %eax
add %0x1, %eax	
	mov %eax, 0x123
mov %eax, 0x123	

NON-DETERMINISM

Concurrency leads to non-deterministic results

- Different results even with same inputs
- race conditions

Whether bug manifests depends on CPU schedule!

How to program: imagine scheduler is malicious?!

WHAT DO WE WANT?

Want 3 instructions to execute as an uninterruptable group

That is, we want them to be atomic

```
mov 0x123, %eax
add %0x1, %eax
mov %eax, 0x123
```

More general: Need mutual exclusion for critical sections

if thread A is in critical section C, thread B isn't

(okay if other threads do unrelated work)

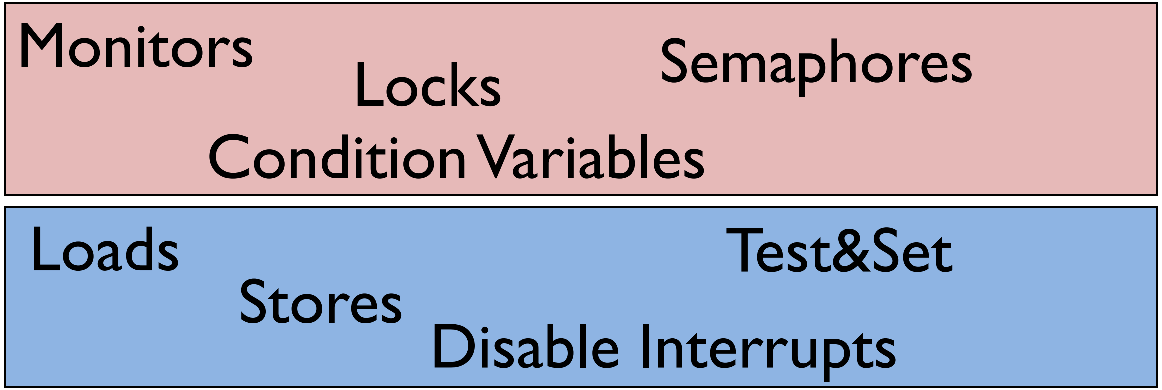
SYNCHRONIZATION

Build higher-level synchronization primitives in OS

Operations that ensure correct ordering of instructions across threads

Use help from hardware

Motivation: Build them once and get them right



LOCKS

LOCKS

Goal: Provide mutual exclusion (mutex)

Allocate and Initialize

- Pthread_mutex_t mylock = PTHREAD_MUTEX_INITIALIZER;

Acquire

- Acquire exclusion access to lock;
- Wait if lock is not available (some other process in critical section)
- Spin or block (relinquish CPU) while waiting
- Pthread_mutex_lock(&mylock);

Release

- Release exclusive access to lock; let another process enter critical section
- Pthread_mutex_unlock(&mylock);

LOCK IMPLEMENTATION GOALS

Correctness

- *Mutual exclusion*
  Only one thread in critical section at a time
- *Progress* (deadlock-free)
  If several simultaneous requests, must allow one to proceed
- *Bounded* (starvation-free)
  Must eventually allow each waiting thread to enter

Fairness: Each thread waits for same amount of time

Performance: CPU is not used unnecessarily

IMPLEMENTING SYNCHRONIZATION

Atomic operation: No other instructions can be interleaved

Approaches

- Disable interrupts
- Locks using loads/stores
- Using special hardware instructions

IMPLEMENTING LOCKS: W/ INTERRUPTS

Turn off interrupts for critical sections

- Prevent dispatcher from running another thread
- Code between interrupts executes atomically

```
void acquire(lockT *l) {
    disableInterrupts();
}
```

```
void release(lockT *l) {
    enableInterrupts();
}
```

Disadvantages?

Only works on uniprocessors

Process can keep control of CPU for arbitrary length

Cannot perform other necessary work

IMPLEMENTING LOCKS: W/ LOAD+STORE

Code uses a single **shared** lock variable

```
// shared variable
boolean lock = false;
void acquire(Boolean *lock) {
    while (*lock) /* wait */ ;
    *lock = true;
}
```

```
void release(Boolean *lock) {
    *lock = false;
}
```

Does this work? What situation can cause this to not work?

RACE CONDITION WITH LOAD AND STORE

```
*lock == 0 initially

Thread 1                        Thread 2
while(*lock == 1)
                                    while(*lock == 1)
                                    *lock = 1
*lock = 1
```

Both threads grab lock!

Problem: Testing lock and setting lock are not atomic

NEXT STEPS

Project 4: Out now

Midterm 1: Next week

Next class: More about locks!