Final Exam

+ Logistics

- **Exam: 100 minutes (half an hour longer than midterm)**
  - Covers all materials, emphasizes second half
  - You may bring 1 page (8.5 by 11, two-sided) of notes. It must be hand-written.
- **Disclaimer: this review is not complete.**
  - Not all exam materials are mentioned by this review!
  - We are not even mentioning things from the first half of the semester.
  - This is a survey of topics and some of the core concepts.
  - There are about 55 slides.. so we will be doing on average a slide a minute!!

+ General Tips

- **Read through all questions, do what you think are the easier ones first.**
- **Make sure you have *completed and understood* all the homeworks, recitation exercises, labs and exams.**
- **Use Piazza! Have discussions there with your classmates.**

Machine-Level Programming

+ Machine-Level Programs

- **Basic information about x84-64**
- **Source, assembly, object & machine code**
- **General purpose registers**
- **Data movement instructions.**
  - `movq %rdi, %rsi`
  - `movq (%rdi), %rsi`

Memory Addressing

- General form

D(Rb, Ri, S) **Mem[D + Reg[Rb] + Reg[Ri] * S]**

  - D: Constant "displacement"
  - Rb: Base register: Any of 16 integer registers
  - Ri: Index register: Any, except for **%rsp**
  - S: Scale: 1, 2, 4, or 8

- Special cases: you can omit certain arguments if not needed.

(Rb,Ri)	**Mem[Reg[Rb] + Reg[Ri]]**
D(Rb,Ri)	**Mem[D + Reg[Rb] + Reg[Ri]]**
(Rb,Ri,S)	**Mem[Reg[Rb] + Reg[Ri] * S]**

Address Computation

- **`leaq`** ***`src, dest`***
  - *src* is an address computation expression
  - set *dest* to address denoted by expression

- use case 1
  - Computing addresses without a memory reference
    - E.g., translation of p = &x[i];

- Example

```
char* a2(char* x){
  return &x[2];
}
```

```
leaq 2(%rdi), %rax   # return &x[2]
ret
```

Arithmetic Operations

- Two Operand Instructions:
  - <u>Format</u> <u>Computation</u>
    - **addq** src, dest dest = dest + src
    - **subq** src, dest dest = dest – src
    - **imulq** src, dest dest = dest * src
    - **salq** src, dest dest = dest << src (also called **shlq**)
    - **sarq** src, dest dest = dest >> src (arithmetic)
    - **shrq** src, dest dest = dest >> src (logical)
    - **xorq** src, dest dest = dest ^ src
    - **andq** src, dest dest = dest & src
    - **orq** src, dest dest = dest | src
- Watch out for argument order!

Arithmetic Expression Example

```
long arith (long x, long y, long z){
  long t1 = x + y;
  long t2 = z + t1;
  long t3 = x + 4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

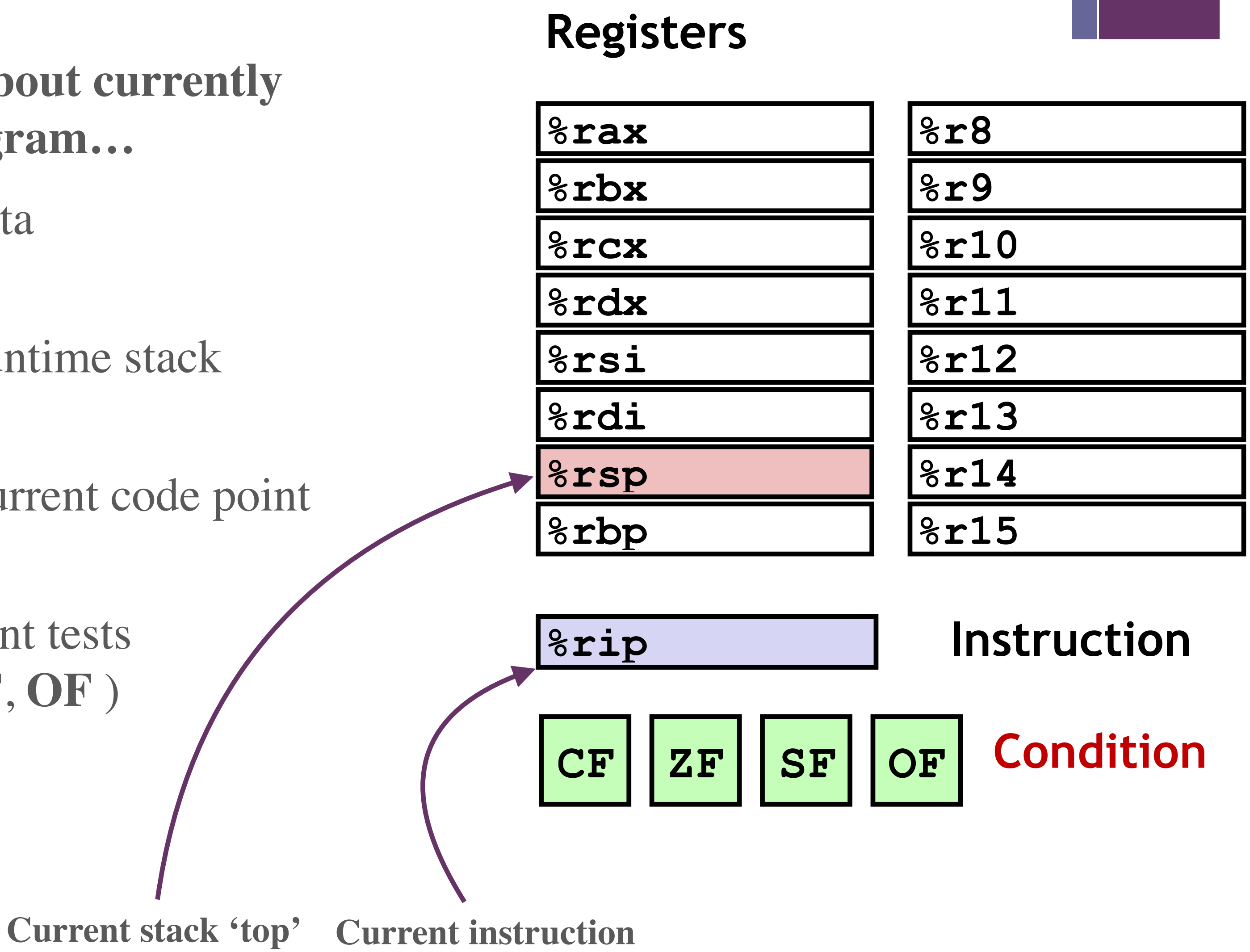
```
arith:
  leaq   (%rdi,%rsi), %rax     #t1
  addq   %rdx, %rax            #t2
  leaq   (%rsi,%rsi,2), %rdx
  salq   $4, %rdx              #t4
  leaq   4(%rdi,%rdx), %rcx    #t5
  imulq  %rcx, %rax            #rval
  ret
```

- Noteworthy instructions:
  - **leaq**: “address” computation
  - **salq**: shift
  - **imulq**: integer multiplication

Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rdx`	Argument **`z`**
`%rax`	`t1`, `t2`, `rval`
`%rdx`	`t4`
`%rcx`	`t5`

Control

- **Information about currently executing program…**
  - temporary data (**%rax**, …)
  - location of runtime stack (**%rsp**)
  - location of current code point (**%rip**)
  - status of recent tests (**CF**, **ZF**, **SF**, **OF**)



Condition Codes (Implicit Setting)

- **Single bit registers**
  - **CF** Carry Flag (for unsigned)
  - **ZF** Zero Flag
  - **SF** Sign Flag (for signed)
  - **OF** Overflow Flag (for signed)
- **Implicitly set (think of it as a side effect) by arithmetic operations**
  - Example: **addq *src*, *dest*** ↔ b = a + b
    - **CF** set if carry out from most significant bit (unsigned overflow)
    - **ZF** set if t == 0
    - **SF** set if t < 0 (as signed)
    - **OF** set if two's-complement (signed) overflow
      $(a > 0 \; \&\& \; b > 0 \; \&\& \; t < 0) \; || \; (a < 0 \; \&\& \; b < 0 \; \&\& \; t > 0)$
- **Not set by leaq instruction (!!!)**

Conditional Branching by Jumping

```c
long absdiff(long x, long y)
{
    long result;
    if (x > y)
        result = x - y;
    else
        result = y - x;
    return result;
}
```

```
absdiff:
   cmpq    %rsi, %rdi  # y, x
   jle     .L4
   movq    %rdi, %rax
   subq    %rsi, %rax
   ret
.L4:               # x <= y
   movq    %rsi, %rax
   subq    %rdi, %rax
   ret
```

Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rax	Return value

+ Conditional Move Example

```
long absdiff(long x, long y){
    long result;
    if (x > y)
        result = x-y;
    else
        result = y-x;
    return result;
}
```

Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rax	Return value
%rdx	Temp variable

```
absdiff:
   movq     %rdi, %rax   # x
   subq     %rsi, %rax   # if-val = x-y
   movq     %rsi, %rdx
   subq     %rdi, %rdx   # else-val = y-x
   cmpq     %rsi, %rdi   # %rsi = y, %rdi = x
   cmovle   %rdx, %rax   # if y <= x, result = else-val
ret
```

+ "Do-While" Loop Compilation

```
long pcount_goto(unsigned long x){
   long result = 0;
 loop:
   result += x & 0x1;
   x >>= 1;
   if(x) goto loop;
   return result;
}
```

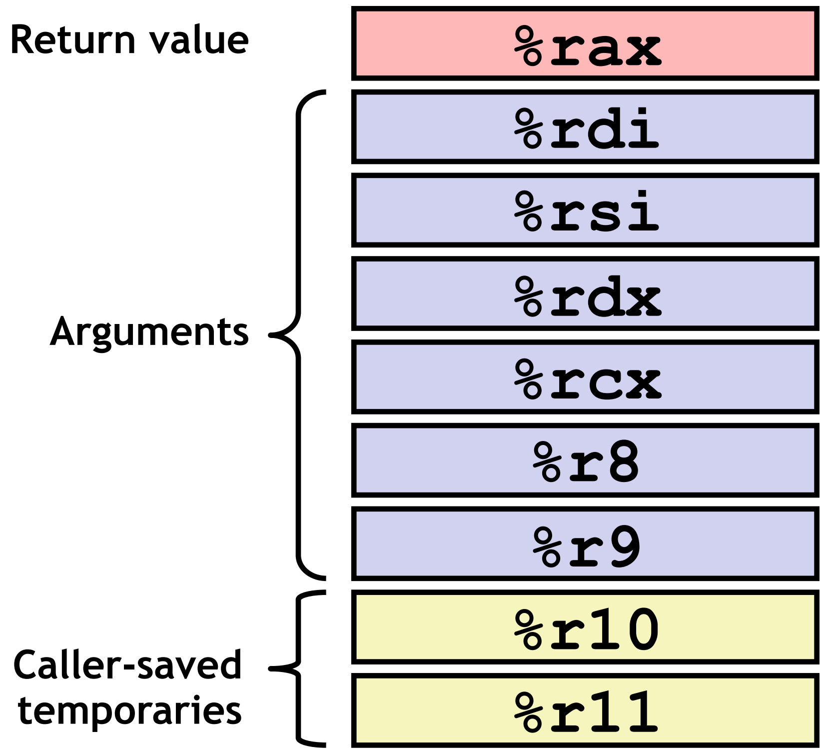
Register	Use(s)
%rdi	Argument x
%rax	result

```
    movl     $0, %rax           #  result = 0
.L2:                            # loop:
    movq     %rdi, %rdx
    andq     $1, %rdx           #  t = x & 0x1
    addq     %rdx, %rax         #  result += t
    shrq     %rdi               #  x >>= 1
    jne      .L2                #  if (x) goto loop
    rep; ret
```

- Note: some processors' branch predictors behave badly when a branch's target or fall-through is a **ret** instruction, and adding the **rep;** prefix avoids this.

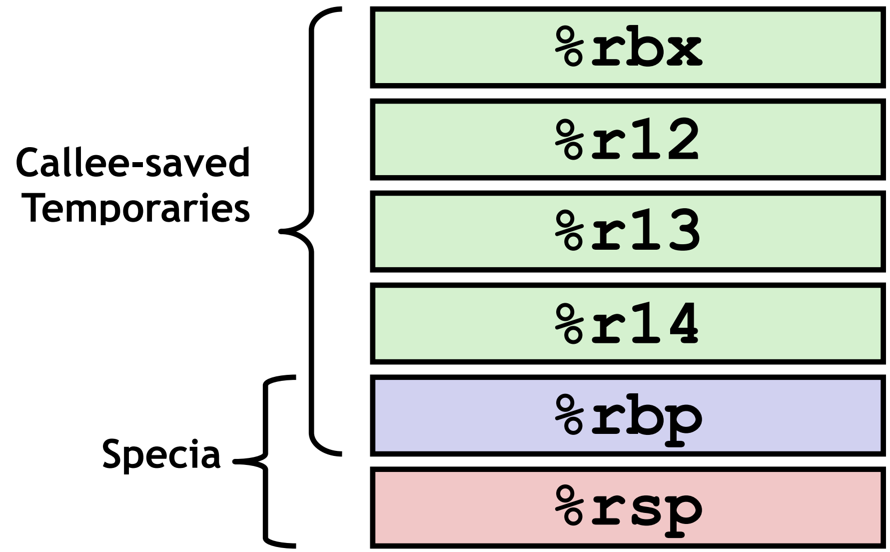
+ x86-64 Caller-saved Registers

- **`%rax`**
  - Return value
  - Also caller-saved
  - Can be modified by procedure
- **`%rdi, ..., %r9`**
  - Arguments
  - Also caller-saved
  - Can be modified by procedure
- **`%r10, %r11`**
  - Caller-saved
  - Can be modified by procedure

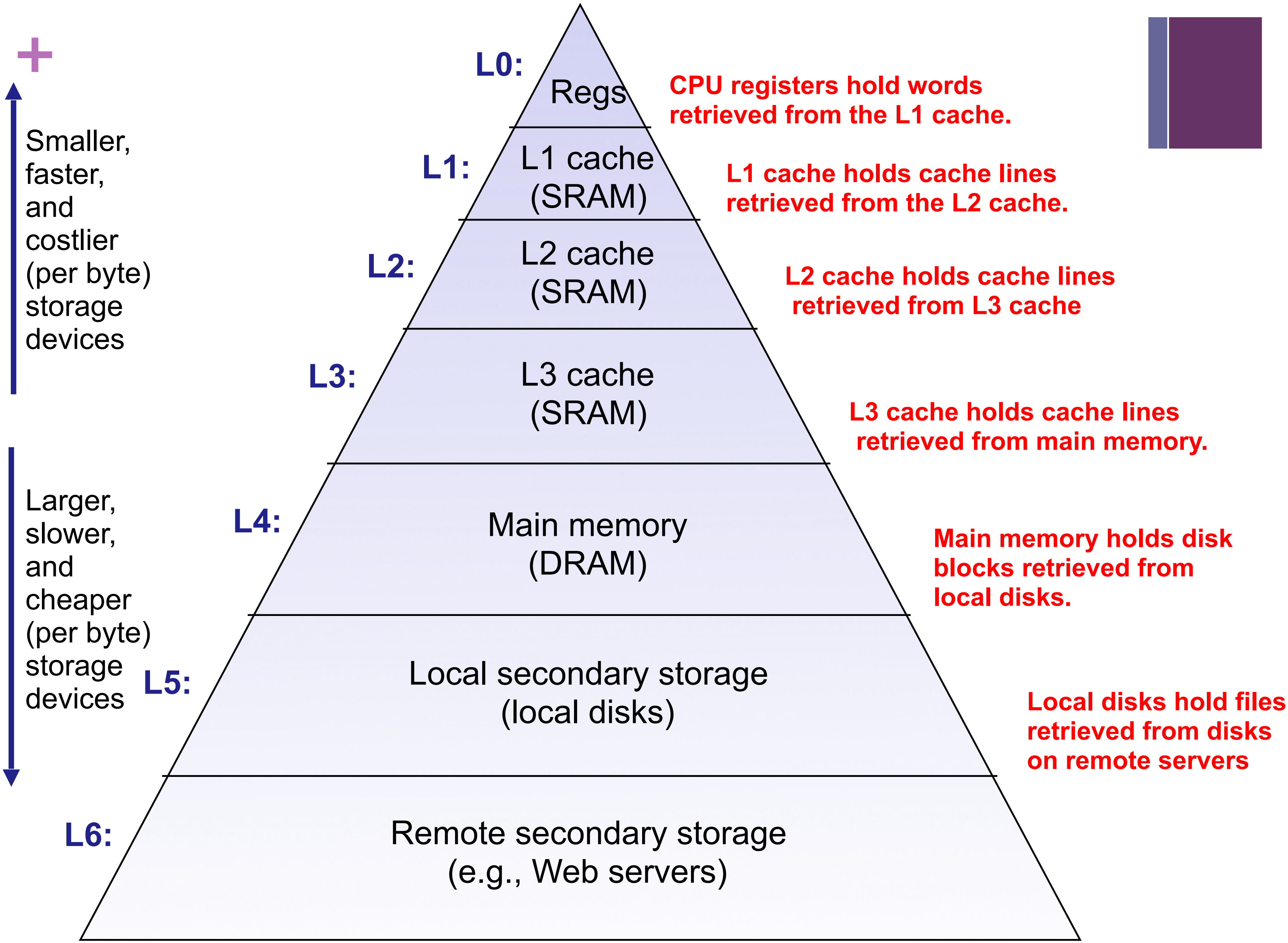


x86-64 Callee-saved Registers

- **`%rbx, %r12, %r13, %r14`**
  - Callee-saved
  - Callee must save & restore
- **`%rbp`**
  - Callee-saved
  - Callee must save & restore
  - May be used as frame pointer
- **`%rsp`**
  - Special form of callee save
  - Restored to original value upon exit from procedure



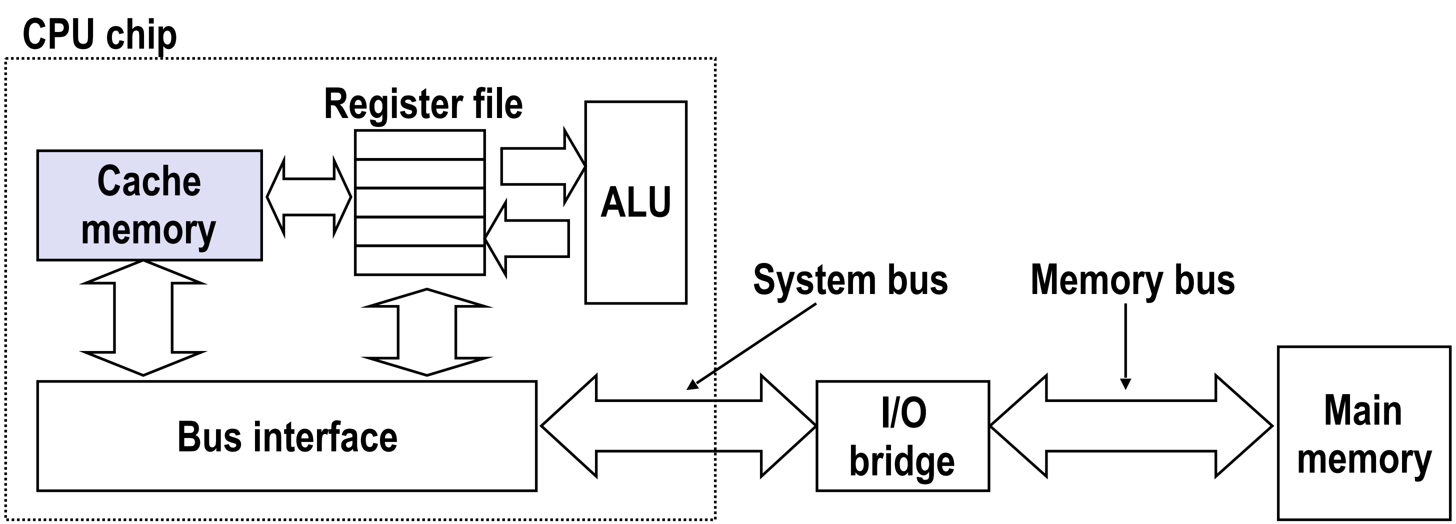
Memory



Smaller,
faster,
and
costlier
(per byte)
storage
devices
Larger,
slower,
and
cheaper
(per byte)
storage
devices
L0:
Regs
L1:
L1 cache
(SRAM)
L2:
L2 cache
(SRAM)
L3:
L3 cache
(SRAM)
L4:
Main memory
(DRAM)
L5:
Local secondary storage
(local disks)
L6:
Remote secondary storage
(e.g., Web servers)
CPU registers hold words retrieved from the L1 cache.
L1 cache holds cache lines retrieved from the L2 cache.
L2 cache holds cache lines retrieved from L3 cache
L3 cache holds cache lines retrieved from main memory.
Main memory holds disk blocks retrieved from local disks.
Local disks hold files retrieved from disks on remote servers

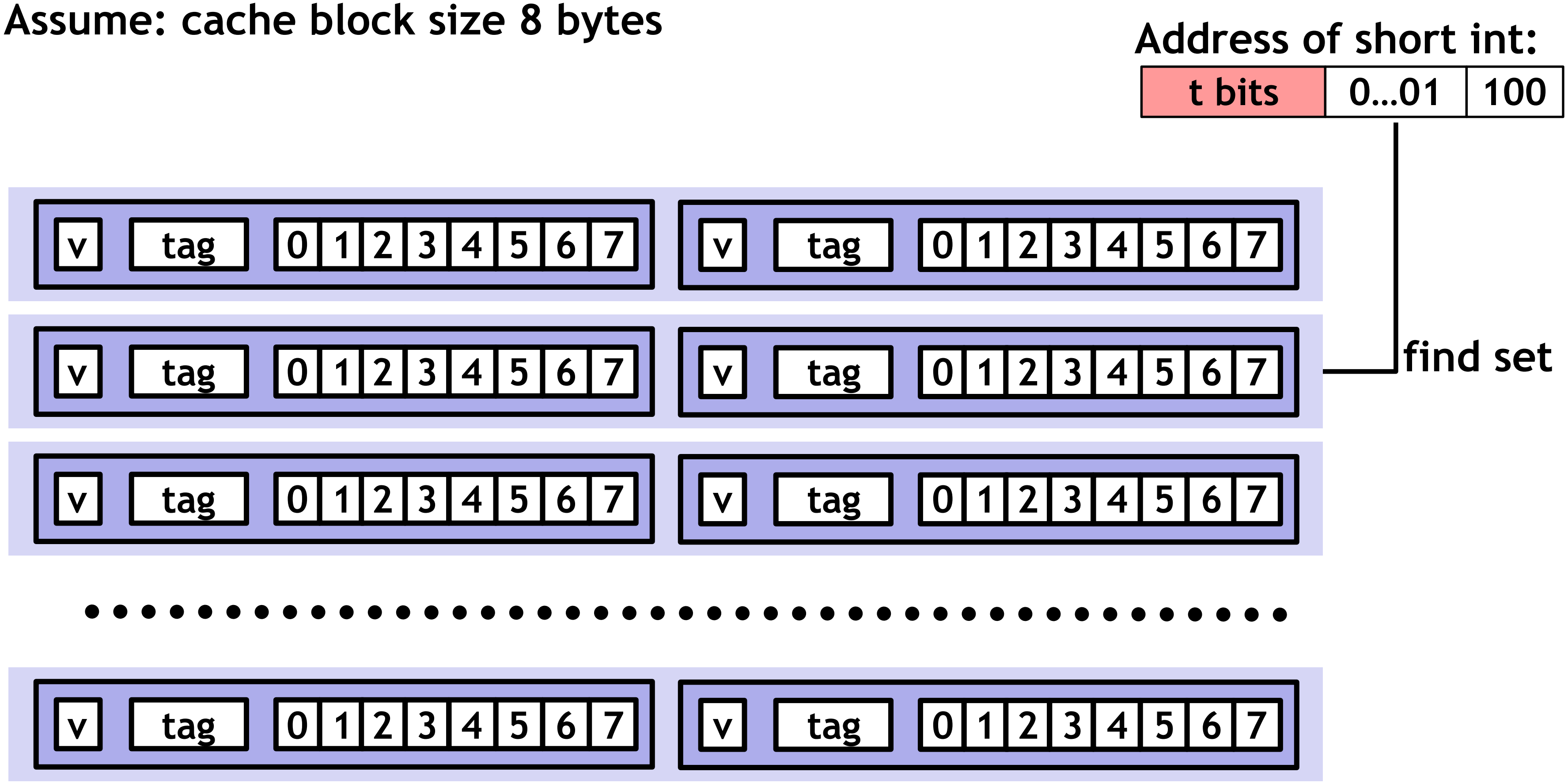
+ Cache Memories

- **Cache memories are small, fast SRAM-based memories managed automatically in hardware**
  - Hold frequently accessed blocks of main memory
- **CPU looks first for data in cache**
- **Simplified system structure:**



+ E-way Set Associative Cache (E = 2)

E = 2: Two lines per set
Assume: cache block size 8 bytes



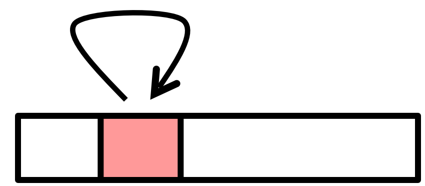
+ Cache Performance Metrics

- **Miss Rate**
  - Fraction of memory references not found in cache (misses / accesses) = 1 – hit rate
  - Typical numbers:
    - 3-10% for L1
    - < 1% for L2, depending on size, etc.
- **Hit Time**
  - Time to deliver a line in the cache to the processor
    - includes time to determine whether the line is in the cache
  - Typical numbers:
    - 4 clock cycle for L1
    - 10 clock cycles for L2
- **Miss Penalty**
  - Additional time required because of a miss
    - typically 50-200 cycles for main memory

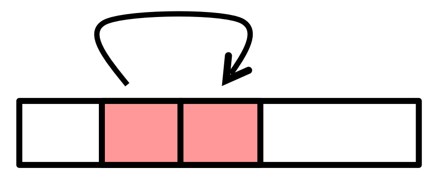
Locality

- **Principle of Locality:** Programs tend to use data and instructions with addresses near or equal to those they have used recently

- **Temporal locality:**
  - Recently referenced items are likely to be referenced again in the near future



- **Spatial locality:**
  - Items with nearby addresses tend to be referenced close together in time

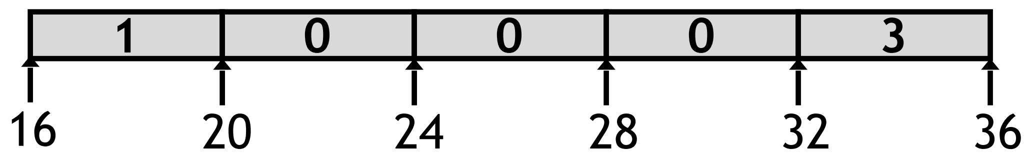


+ Stride-n Access Patterns

- **C arrays allocated in row-major order, contiguously**
- **Stepping through columns in one row:**
  - ```
    for (i = 0; i < N; i++)
        sum += a[0][i];
    ```
  - accesses successive, contiguous elements
- **Stepping through rows in one column:**
  - ```
    for (i = 0; i < n; i++)
       sum += a[i][0];
    ```
  - accesses distant elements (stride-rowsize pattern)
  - no spatial locality!

+ Array Accessing Example

`int[] nyu;`



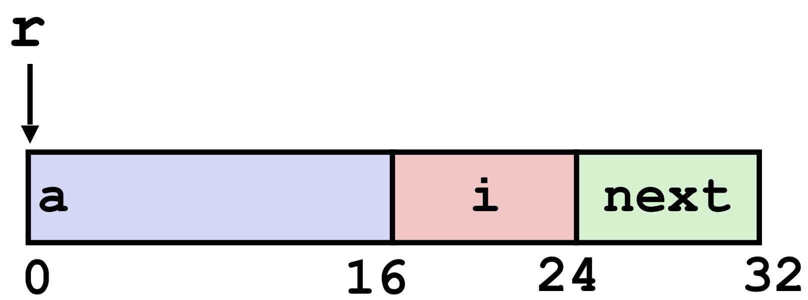

```
int get_digit(int[] z, int digit){
  return z[digit];
}
```

```
# %rdi = z
# %rsi = digit
movq (%rdi,%rsi,4), %rax  # z[digit]
```

- Register **`%rdi`** contains starting address of array
- Register **`%rsi`** contains array index
- Desired digit at **`%rdi + 4*%rsi`**
- Use memory reference **`(%rdi,%rsi,4)`**

+ Structure Representation

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
```

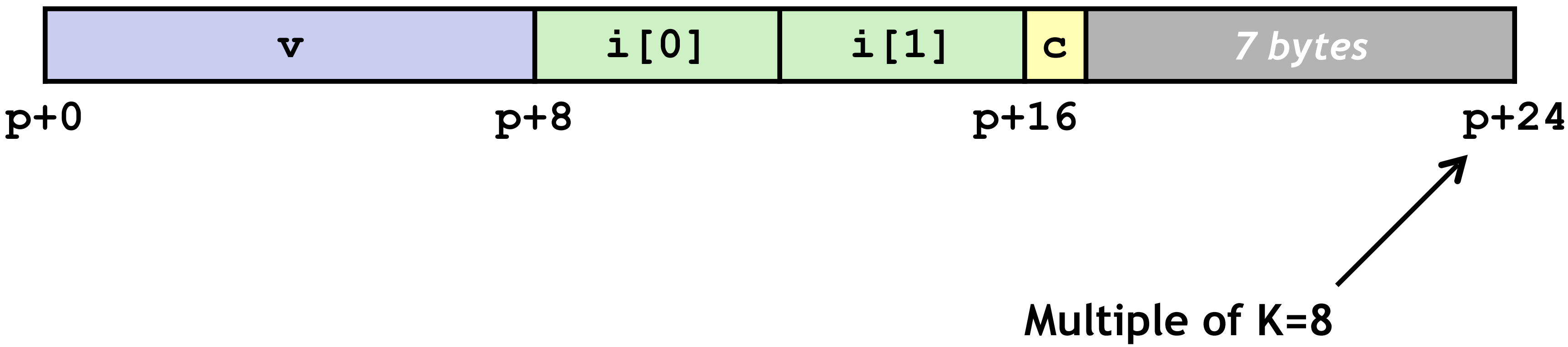


- **Structure represented as block of memory**
  - Big enough to hold all of the fields
- **Fields ordered according to declaration**
  - Even if another ordering could yield a more compact representation
  - Machine-level program has no understanding of the structures in the source code

Alignment Requirement

- For largest alignment requirement K
- Overall structure must be multiple of K

```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



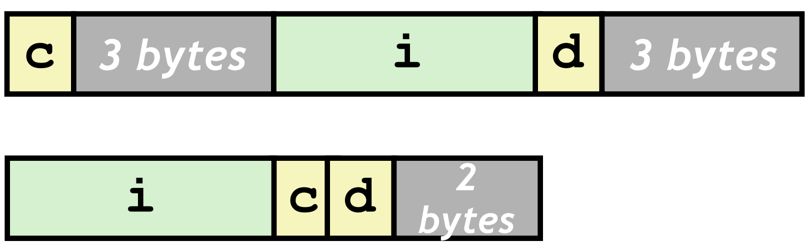
+ Saving Space (Struct packing)

- Put large data types first

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```

- Effect (K=12 -> K=4)



Exceptions & Processes

+ Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's control flow (or flow of control)

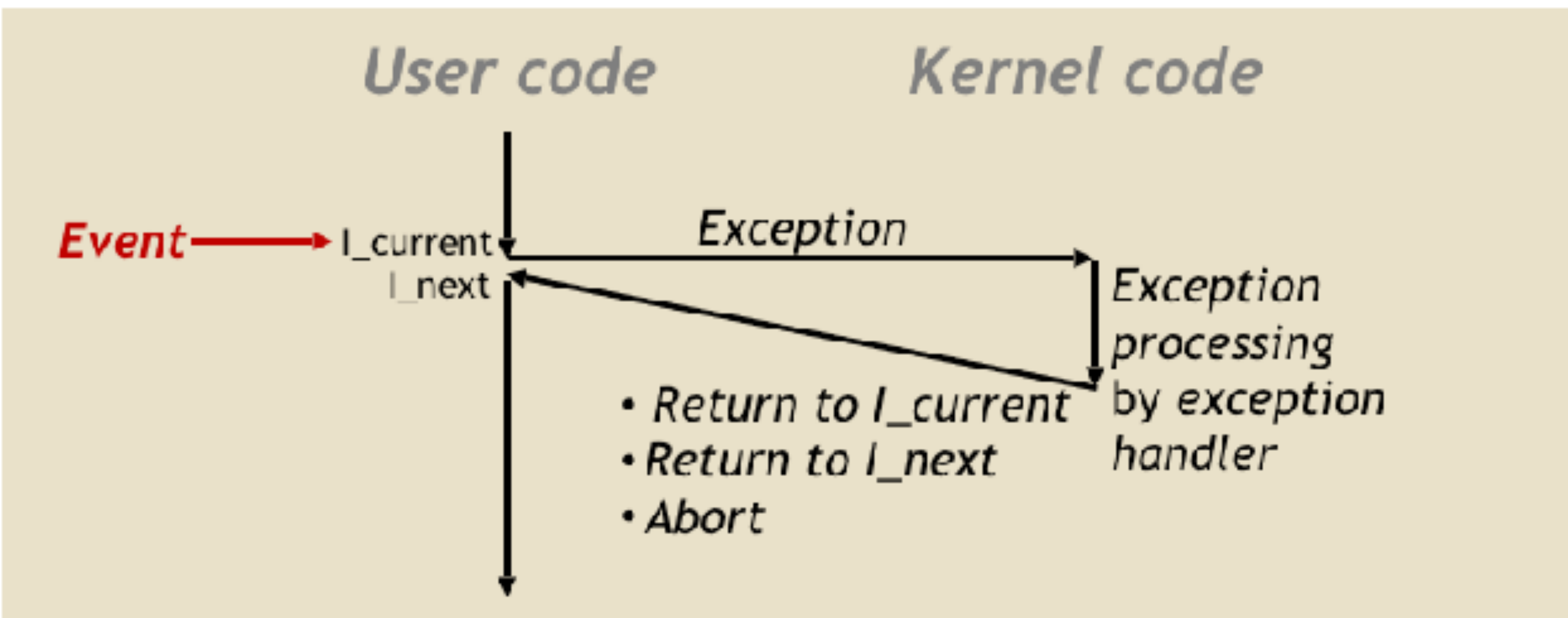
Control flow

Time

<startup>
inst$_1$
inst$_2$
inst$_3$
…
inst$_n$
<shutdown>

Exceptions

- **An exception is a transfer of control to the OS kernel in response to some event (i.e., change in processor state)**
  - Examples of events: Divide by 0, page fault, I/O request completes, typing Ctrl-C



+ Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor's *interrupt pin*
  - Handler returns to "next" instruction

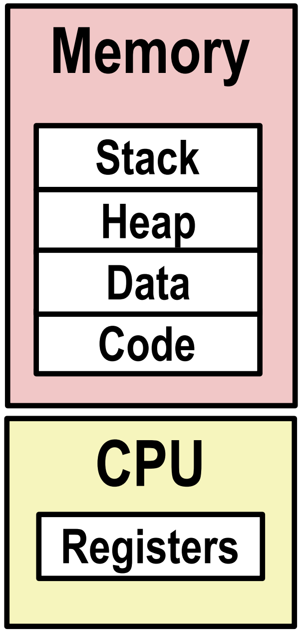
- **Examples**:
  - *Timer interrupt*
    - Every few ms, an external timer chip triggers an interrupt
    - Used by the kernel to take back control from user programs
  - *I/O interrupt from external device*
    - Arrival of a packet from a network
    - Arrival of data from a disk

+ Synchronous Exceptions

- **Caused by events that occur as a result of executing an instruction:**
  - *Traps*
    - Intentional
    - Example: *system calls*
    - Returns control to “next” instruction
  - *Faults*
    - Unintentional but possibly recoverable
    - Example: *page fault*
    - Either re-executes faulting (“current”) instruction or aborts
  - *Aborts*
    - Unintentional and unrecoverable
    - Example: *illegal memory access*
    - Aborts current program

+ Processes

- **A *process* is an instance of a running program.**
  - One of the most successful ideas in computer science
  - Not the same as "program"
- **Process provided with two key abstractions by OS:**
  - *Logical control flow*
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called *context switching*
  - *Private address space*
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*



+ Creating and Terminating Processes

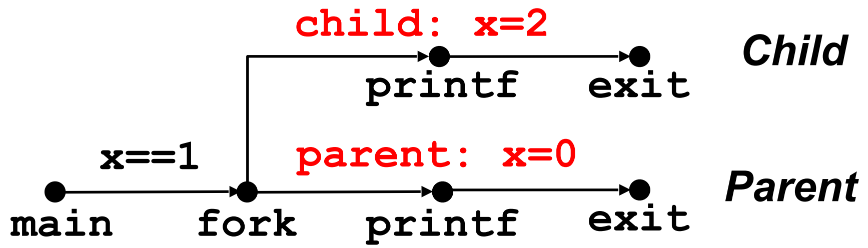
- **From a programmer's perspective, we can think of a process as being in one of three states**
- **Running**
  - Process is either executing, or waiting to be executed and will eventually be scheduled (i.e., chosen to execute) by the kernel
- **Stopped**
  - Process execution is suspended and will not be scheduled until further notice
- **Terminated**
  - Process is stopped permanently
  - Zombie!

+ Process Management

- **Creating processes**
  - Call `fork`
  - One call, *two* returns
- **Process completion**
  - Call `exit`
  - One call, no return
- **Reaping and waiting for processes**
  - Call `wait` or `waitpid`
- **Loading and running programs**
  - Call `execve`
  - One call, no return

Process Graph Example

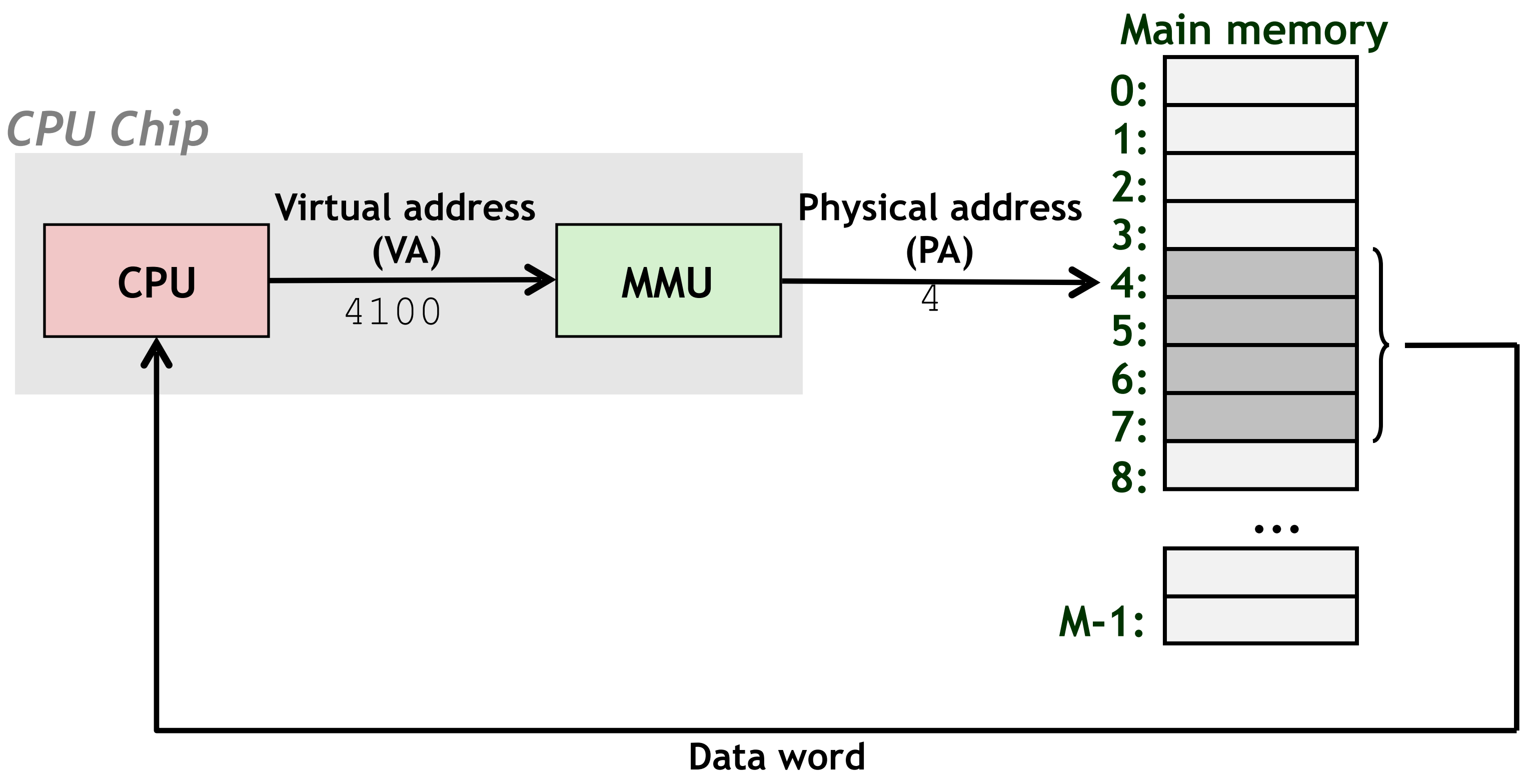
```c
int main() {
    pid_t pid;
    int x = 1;

    pid = fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```



Virtual Memory

Virtual Addressing

- Creates illusion to process that it has total address space.
- Used in all modern, non-trivial systems

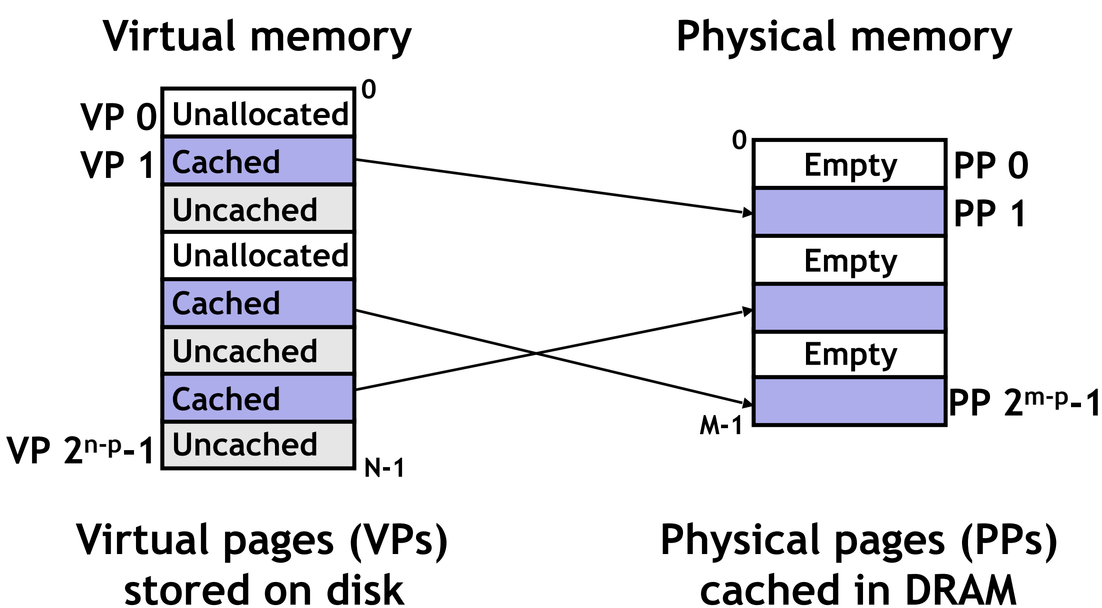


+ Why Virtual Memory (VM)?

- **Uses main memory efficiently**
  - Use DRAM as a cache for parts of a virtual address space
- **Simplifies memory management**
  - Each process gets the same uniform linear address space
- **Isolates address spaces**
  - One process can't interfere with another's memory
  - User program cannot access privileged kernel information and code

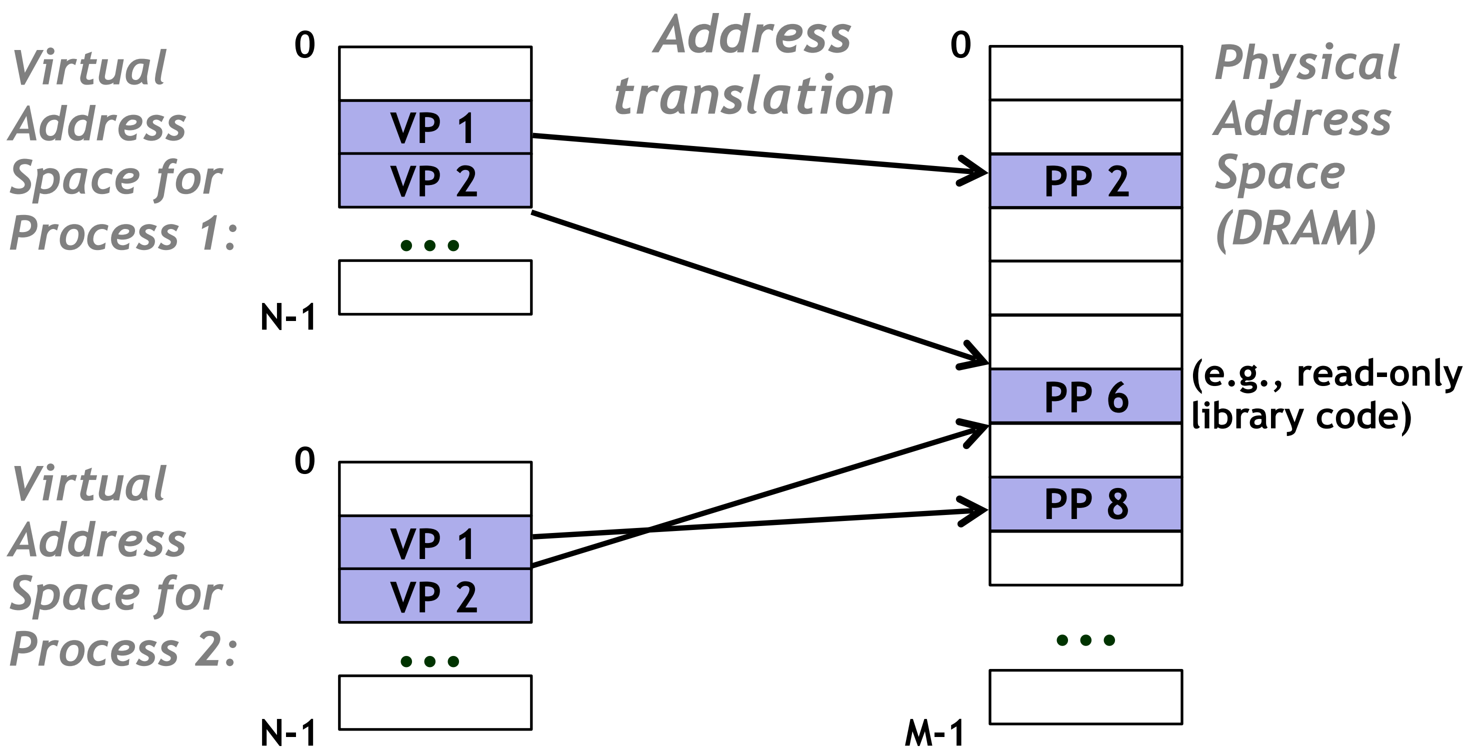
+ VM as Caching

- **Conceptually, virtual memory is an array of N contiguous bytes stored on disk.**
- **The contents of the array on disk are cached in physical memory**
  - These cache blocks are called *pages*



+ VM as a Tool for Memory Management

- **Key idea: each process has its own virtual address space**
  - It can view memory as a simple linear array
  - Mapping function scatters addresses through physical memory

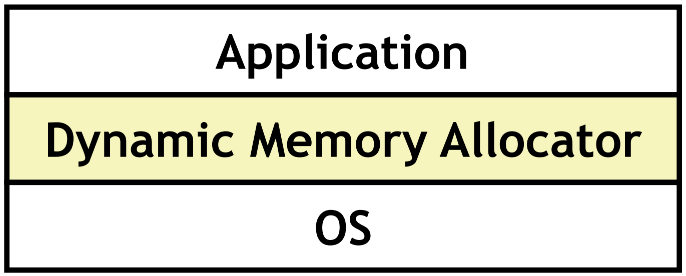


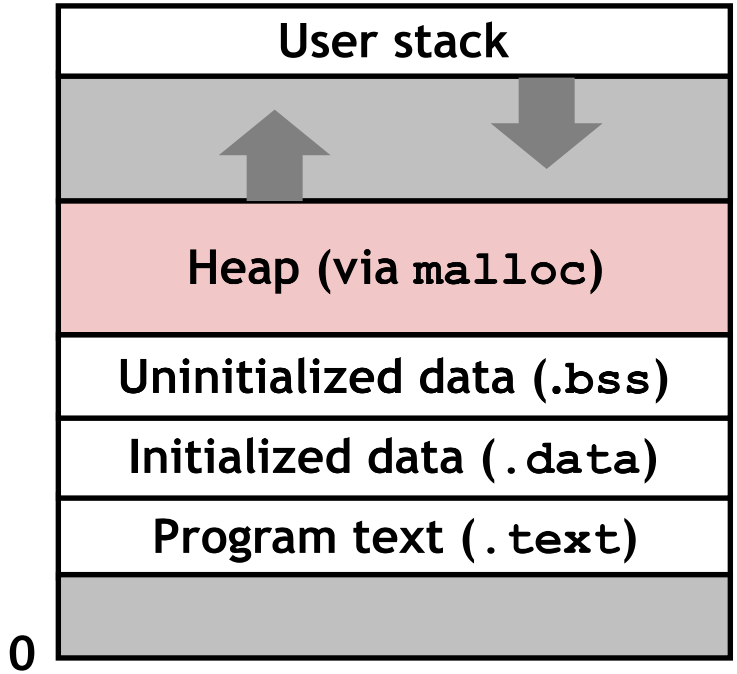
Dynamic Allocation

+ Dynamic Memory Allocators

- **Programmers use dynamic memory allocators to acquire virtual memory at run time.**
  - For data structures whose size is only known at runtime.

- **Dynamic memory allocators manage an area of process virtual memory known as the heap.**





+ Constraints

- **Applications**
  - Can issue arbitrary sequence of `malloc` and `free` requests
  - `free` request must be to a `malloc`'d block
- **Allocators**
  - Can't control number or size of allocated blocks
  - Can't reorder or buffer requests for memory
  - Must allocate blocks from *free* memory
  - Can manipulate and modify only *free* memory
  - Can't move the allocated blocks once they are `malloc'd`

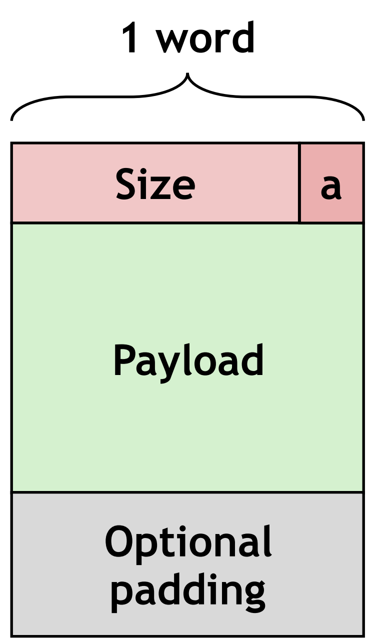
+ Performance Goals

- **Goal: Increase utilization (by reducing fragmentation)**
  - internal fragmentation
  - external fragmentation
- **Goal: Maximize throughput:**
  - Number of completed requests per unit time
  - Example:
    - 5,000 `malloc` calls and 5,000 `free` calls in 10 seconds
    - Throughput is 1,000 operations/second

+ Implicit Lists

- **For each block we need both size and allocation status**
  - Could store this information in two words: wasteful!
- **Standard trick**
  - If blocks are word-aligned, some low-order address bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
  - *(Note: when reading size, must mask out any extra bits)*

Format of allocated and free blocks

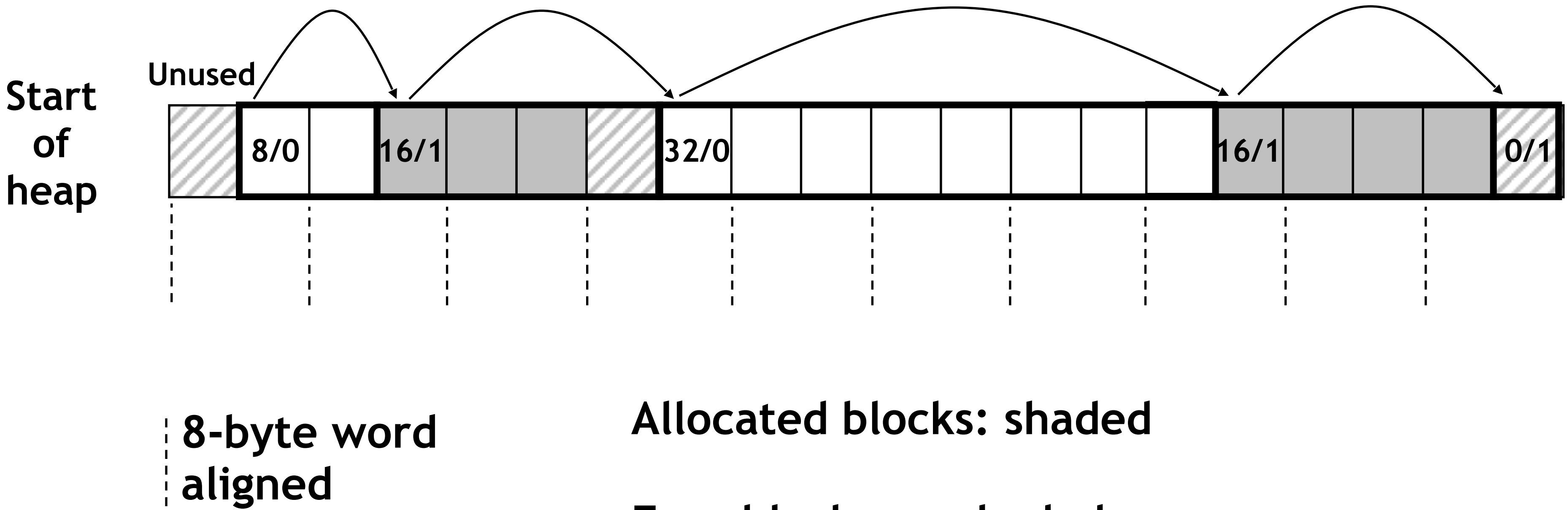


a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data
(allocated blocks only)

+ Detailed Implicit Free List Example



Allocated blocks: shaded

Free blocks: unshaded

Headers: labeled with size in bytes/allocated bit

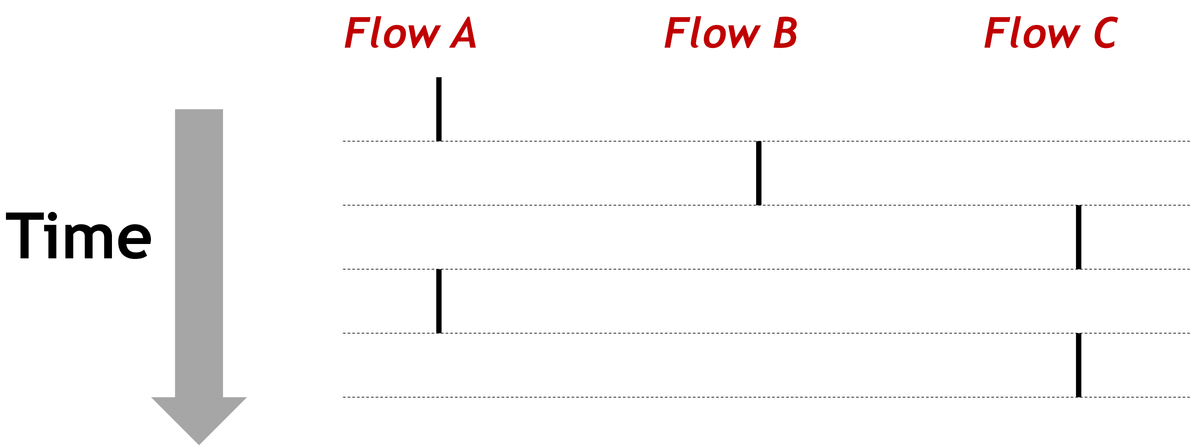
Ideas to remember…

- **Allocation**
- **Freeing**
- **Fragmentation**
  - External
  - Internal
- **Coalescing**

+ Concurrent Programming

+ Concurrency

- **Multiple logical control flows.**
- **Flows run concurrently if they overlap in time**
  - Otherwise, they are sequential
- **Examples (running on single core):**
  - Concurrent: A & B, A & C
  - Sequential: B & C



+ Process Concurrency

- **Use fork to launch multiple processes to do work.**
  - Hard for them to share data. Must use IPC.
- **How to communicate across processes? (*inter-process communication or IPC*)**
  - via *sockets*
  - via *pipes*
  - via *shared memory objects*

+ Thread-based Concurrency

- **A thread is…**
  - a unit of execution, associated with a process.
  - the smallest sequence of instructions that can be managed independently by the OS scheduler

- **Multiple threads can..**
  - exist within one process
  - be executing concurrently
  - *share resources* such as memory

+ Threads vs. Processes

- **Similarities**
  - Each has its own logical control flow
  - Each can run concurrently (possibly on different cores)
  - Each is context switched
- **Differences**
  - Threads share all code and data (except local stacks)
    - Processes do not
  - Threads are somewhat less expensive than processes
    - Process control (creating/reaping) ***2x*** as expensive as thread control

+ Concurrent Programming is Hard!

- **The ease with which threads share data and resources also makes them vulnerable to subtle and baffling errors.**
- **Classical problem classes of concurrent programs:**
  - *Races*: outcome depends on arbitrary scheduling decisions elsewhere in the system

Race Example

- **What's the expected output on line 11?**
  - 2
- **Possible output…**
  - 1

```
1  int numbers[2] = { 1, 1 };
2  int sum = 0;
3
4  int main() {
5    pthread_t tid;
6    pthread_create(&tid,NULL,run,numbers[1]);
7    for (int i = 0; i < 1; i++) {
8        sum += numbers[i];
9    }
10   pthread_join(tid, NULL);
11   printf("sum is %d\n", sum);
12 }
13
14 void* run(void* arg) {
15   int* numbers = (int*) arg;
16   for (int i = 0; i < 1; i++) {
17       sum += numbers[i];
18   }
19   return NULL;
20 }
```

+ Synchronizing Threads

- **Shared variables are sometimes useful but they introduce the possibility of *synchronization* errors.**
  - Like the one we saw last time
- **How do we prevent such things?**
  - We need to make sure that only one thread is executing "critical sections" (usually mutating shared variables!)
  - This is known as *mutual exclusion*
- **Moreover, we must protect *critical sections*.**
- **AGAIN, MULTIPLE THREADS WRITING TO THE EXACT SAME LOCATION IN MEMORY CONCURRENTLY IS A BAD THING!**

+ Mutual Exclusion

- **A *mutex*…**
  - is synchronization variable that is used to protect the access to shared variables.
  - surrounds critical sections so that one threads is allowed inside at a time.
- **However we have to be careful with these because they can lead to code that performs poorly, or in some cases not at all…**