Final Exam

Logistics

- **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.

+ 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, quizzes 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)`
    - **`xorg`** `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;
}
```

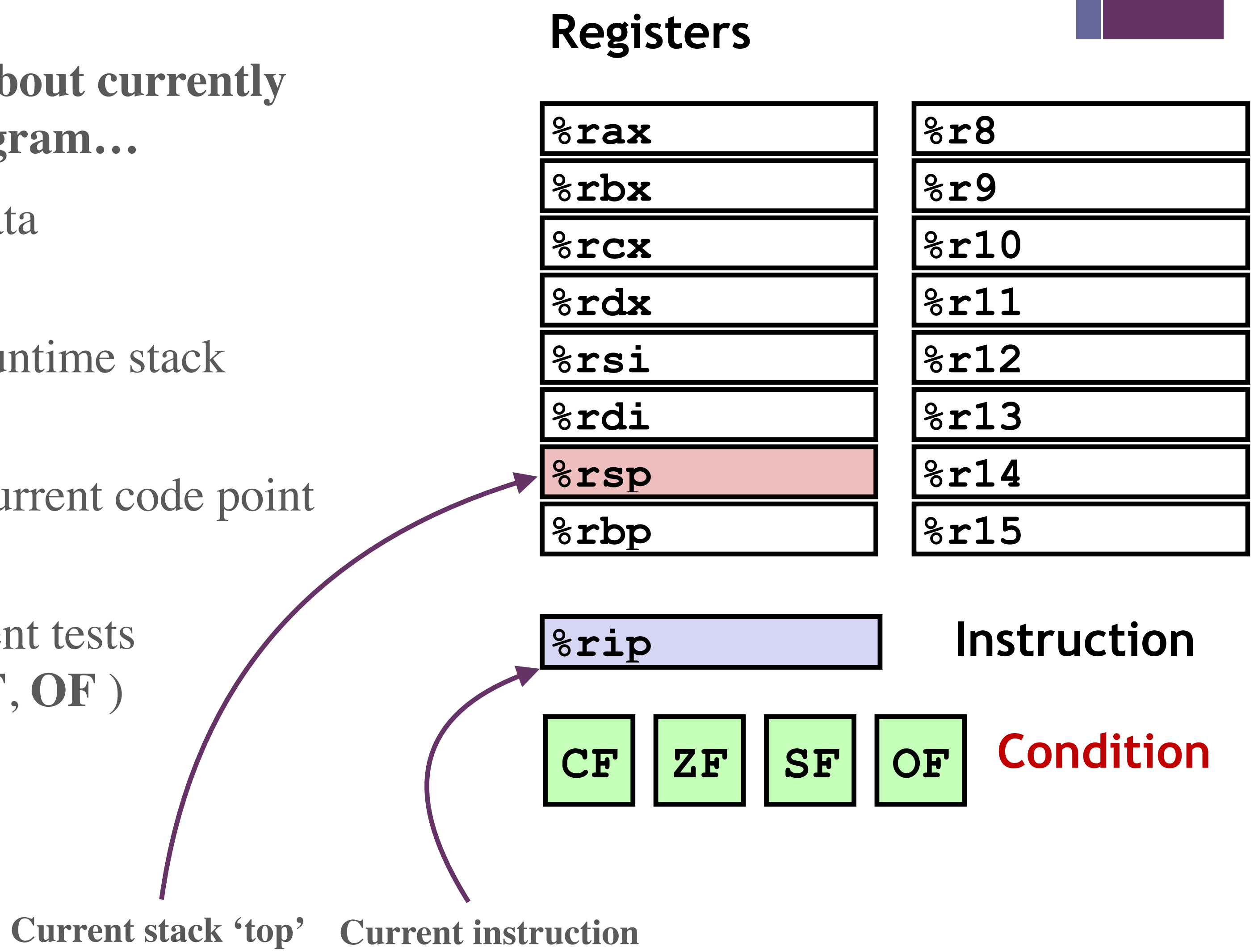
```
arith:
  leaq   (%rdi,%rsi), %rax      #t1
  addq   %rdx, %rax             #t2
  leaq   (%rsi,%rsi,2), %rdx
  salq   $4, %rdx               #t4
  leaq   4(%rdi,%rdx), %rcx     #t5
  imulq  %rcx, %rax             #rval
  ret
```

- 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.

+ Procedure Data Flow

Registers

First 6 arguments

`%rdi`
`%rsi`
`%rdx`
`%rcx`
`%r8`
`%r9`

Return value

`%rax`

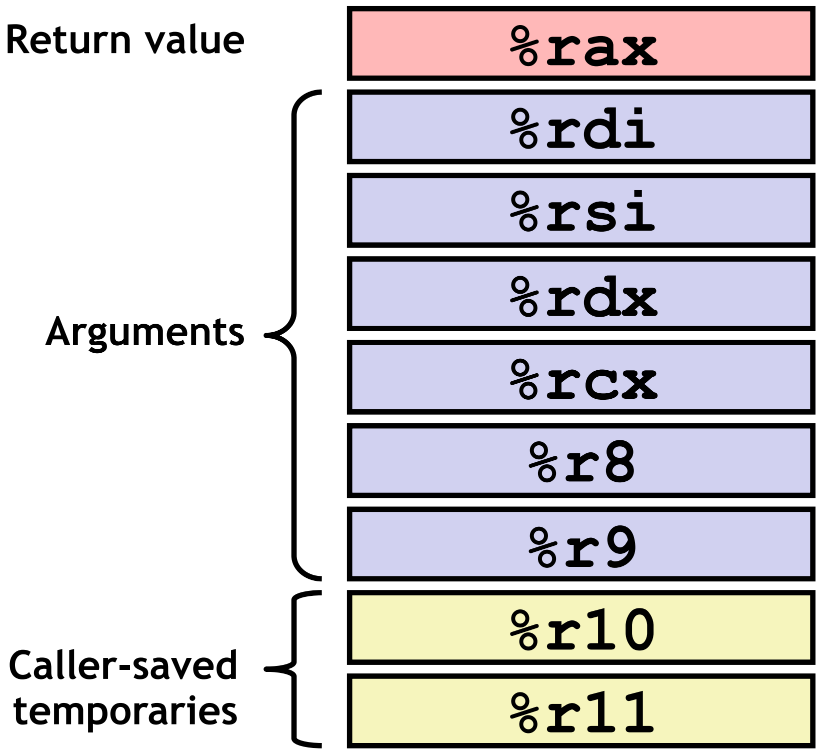
Stack

• • •
Arg *n*
• • •
Arg 8
Arg 7

- Only allocate stack space when needed

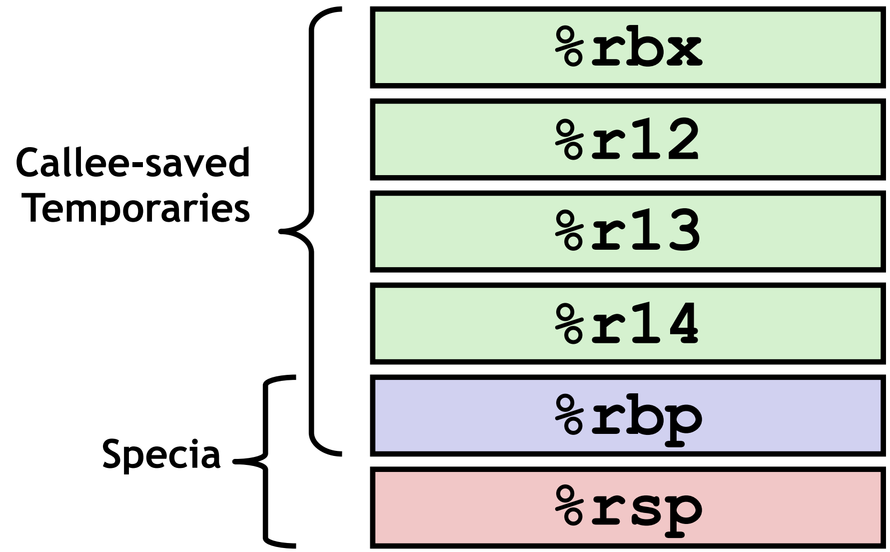
x86-64 Caller-saved Registers

- **`%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

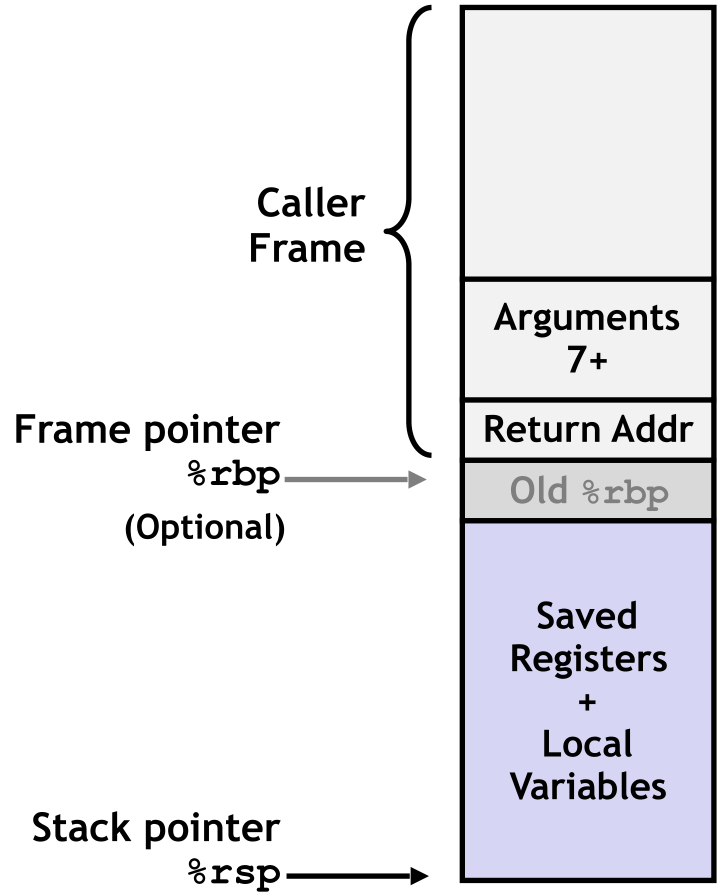
- **`%rbx, %r12, %r13, %r14`**
  - Callee-saved
  - Callee must save & restore
- **`%rbp`**
  - Callee-saved
  - Callee must save & restore
  - May be used as frame pointer
- **`%rsp`**
  - Special form of callee save
  - Restored to original value upon exit from procedure



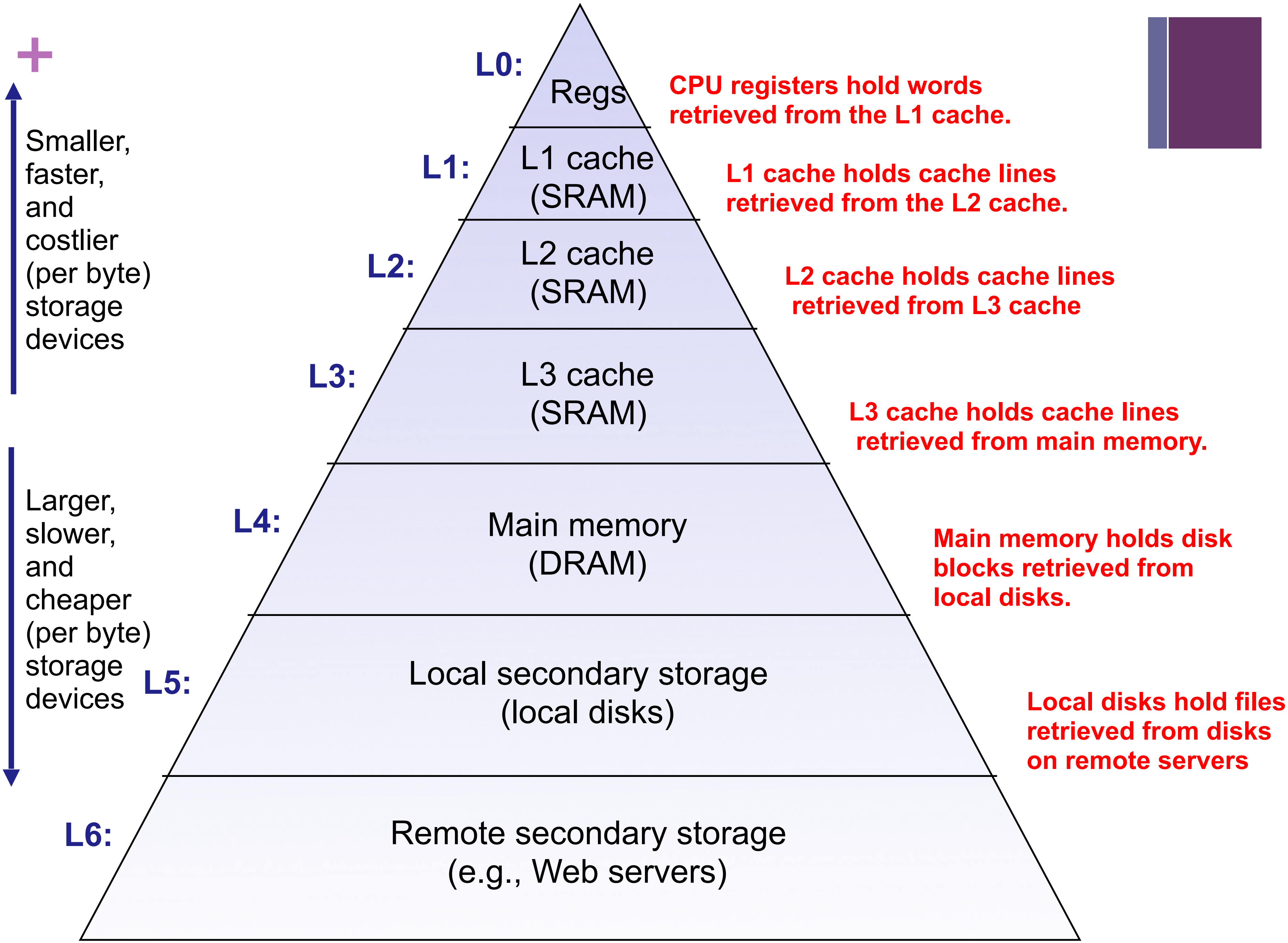
+ x86-64/Linux Stack Frame

- **Current Stack Frame ('Top' to 'Bottom')**
  - *Local variables*
    If can't keep in registers
  - *Old frame pointer* (optional)

- **Caller Stack Frame**
  - Return address
    - Pushed by **`call`** instruction
  - Arguments for this call



Memory

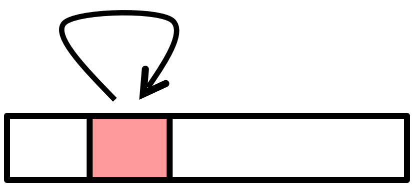


L0:
Regs
CPU registers hold words retrieved from the L1 cache.
L1:
L1 cache (SRAM)
L1 cache holds cache lines retrieved from the L2 cache.
L2:
L2 cache (SRAM)
L2 cache holds cache lines retrieved from L3 cache
L3:
L3 cache (SRAM)
L3 cache holds cache lines retrieved from main memory.
L4:
Main memory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

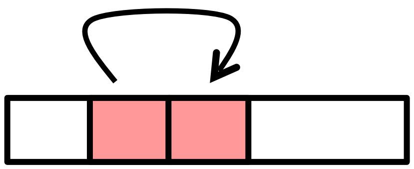
+ Locality

- **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

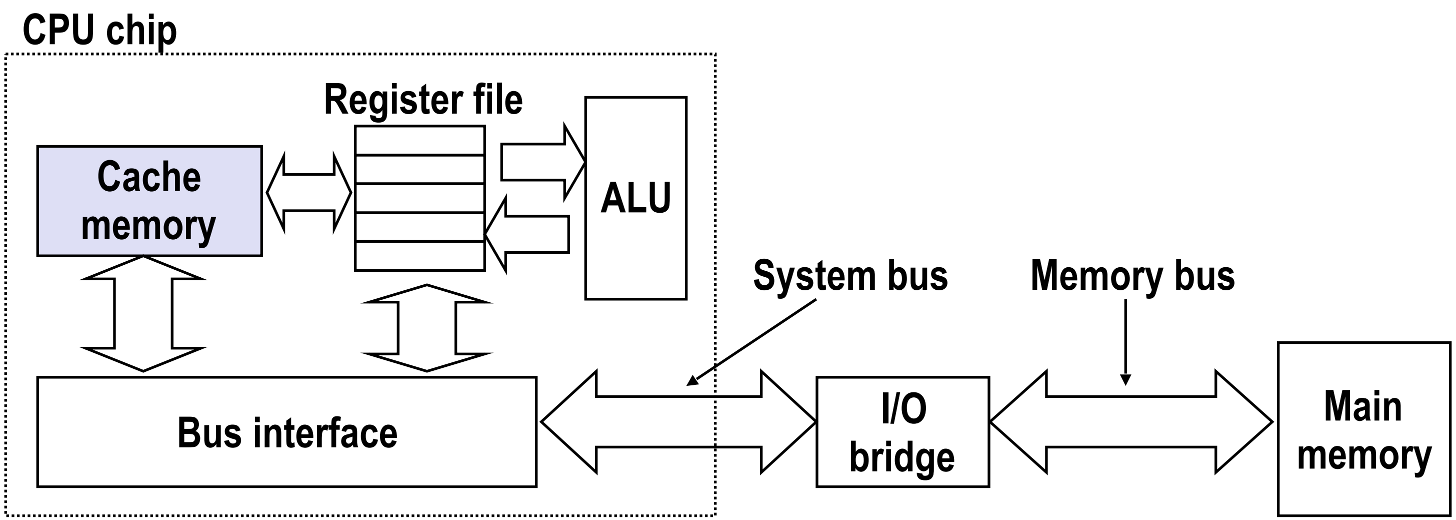


- **Spatial locality:**
  - Items with nearby addresses tend to be referenced close together in time



+ 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**
- **Typical system structure:**



+ 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!

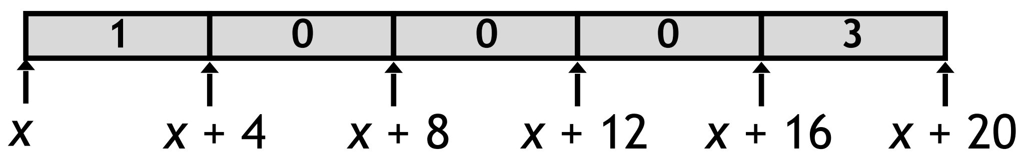
+ Array Access

- **Basic Principle**

  T **A[*N*];**

  - Array of data type ***T*** and length ***N***
  - Identifier ***A*** can be used as a pointer to array element 0: type ***T****

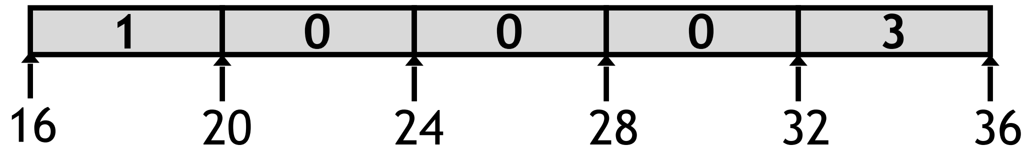
`int val[5];`



Reference	Type	Value
`val[4]`	`int`	3
`val`	`int*`	*x*
`val+1`	`int*`	*x* + 4
`&val[2]`	`int*`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	0
`val + i`	`int*`	*x* + 4 *i*

+ Array Accessing Example

`int[] nyu;`



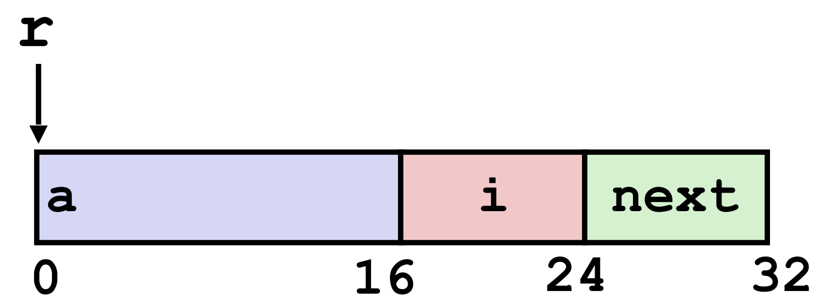

```
int get_digit(int[] z, int digit){
  return z[digit];
}
```

```
# %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

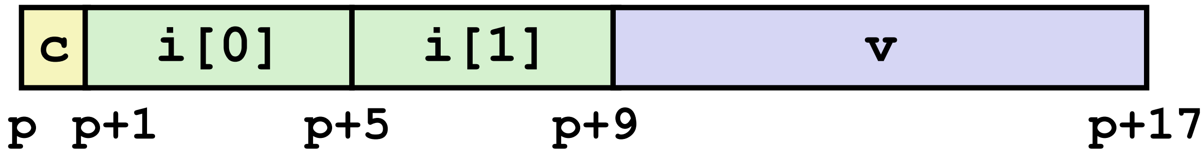
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
```



- **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

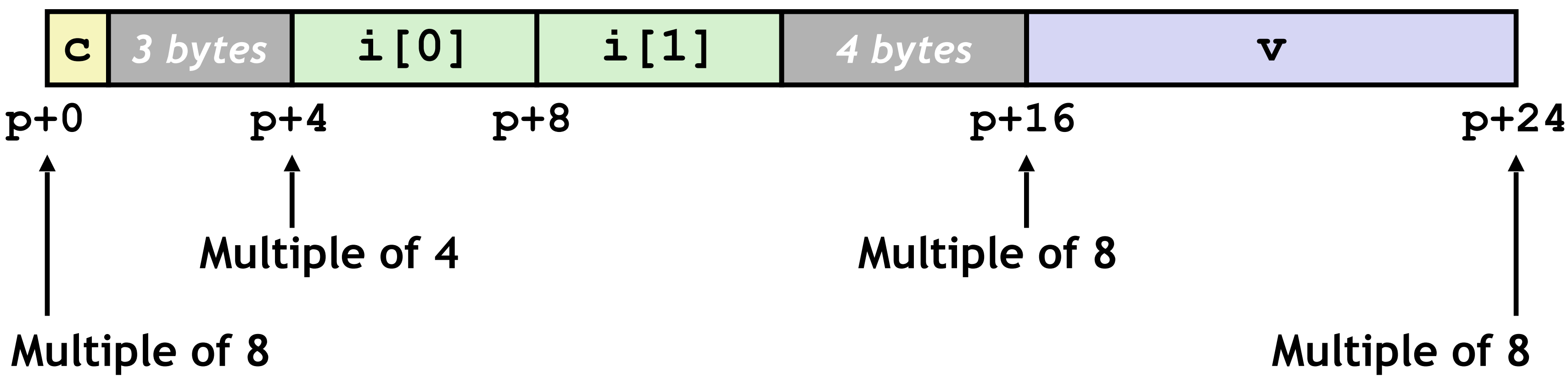
Structures & Alignment

- **Unaligned Data**




```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

- **Aligned Data**
  - Primitive data type requires ***K*** bytes
  - Address must be multiple of ***K***



Linking

+ What Do Linkers Do?

- **Step 1: Symbol resolution**
  - Programs define and reference symbols (global variables and functions):
    - `void swap(){…} /* define symbol swap */`
    - `swap();        /* reference symbol swap */`
    - `int *xp = &x;  /* define symbol xp, reference x */`
  - Symbol definitions are stored in object file in symbol table.
    - Symbol table is an array of structs
    - Each entry includes name, size, and location of symbol.
  - *During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.*

Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules.
  - E.g.: non-static C functions and non-static global variables.
- **External symbols**
  - Global symbols that are referenced by module *m* but defined by some other module.
- **Local symbols**
  - Symbols that are defined and referenced exclusively by module m.
  - E.g.: C functions and global variables with the static attribute.
  - *Local linker symbols are **not** local program variables*

+ Resolving Duplicate Symbol Definitions

- **All symbol references must be mapped to 1 definition.**
  - How to choose when there are duplicates?

- **Taxonomy of symbol definitions aids decision.**

- **Program symbols are either strong or weak**
  - **Strong**: procedures and initialized globals
  - **Weak**: uninitialized globals

	p1.c	p2.c	
strong	`int foo=5;`	`int foo;`	weak
strong	`p1() { }`	`p2() { }`	strong

+ Linker’s Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol and multiple weak symbols, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol
- **Rule 3: If there are multiple weak symbols, pick any one**
  - Can override this with gcc –fno-common
  - Probably a good idea to use above flag

What Do Linkers Do? (*cont*)

- **Step 2: Relocation**

  - Merges separate code and data sections into single sections

  - Relocates symbols from their relative locations in the .o files to their final absolute memory locations in the executable.

  - Updates all references to these symbols to reflect their new positions.

+ When Can Linking Happen?

- **Linking can happen at different times in a program's lifetime:**
  - Compile time (when a program is compiled)
  - Load time (when a program is loaded into memory)
  - Run time (while a program is executing)

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)

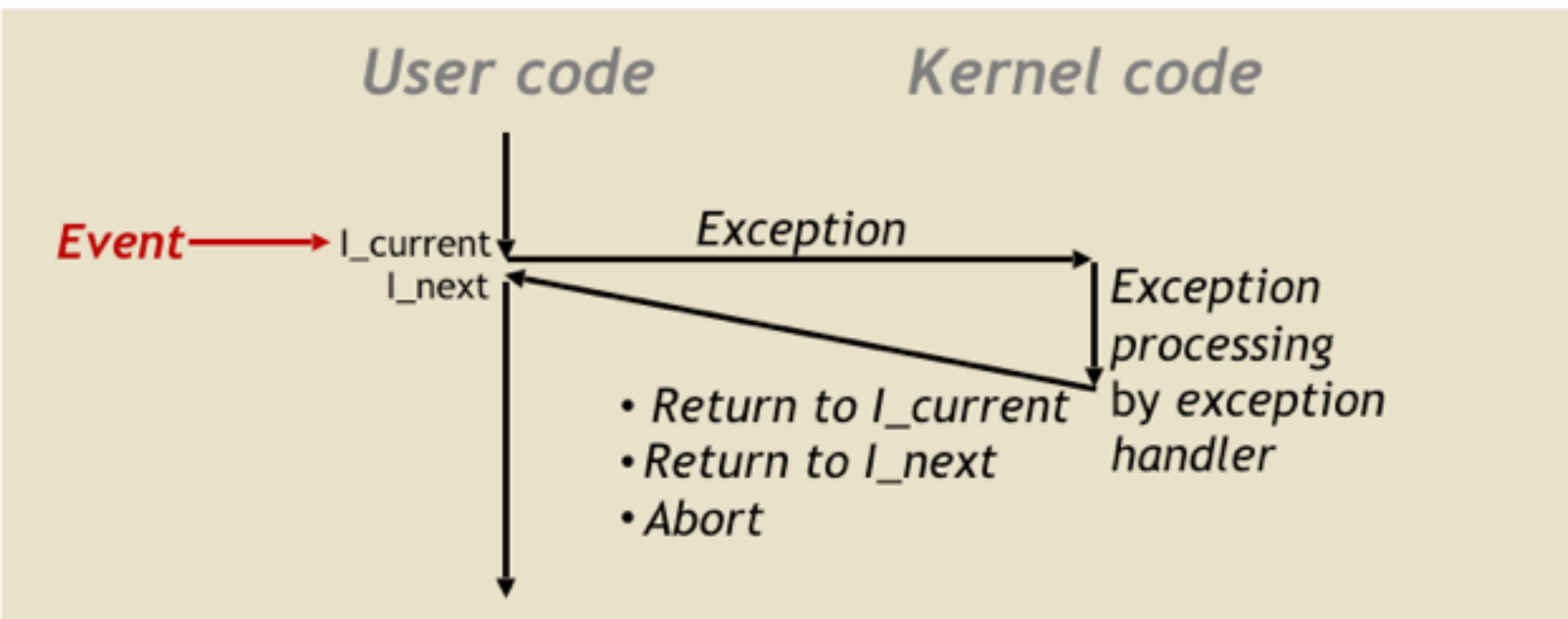
Control flow

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

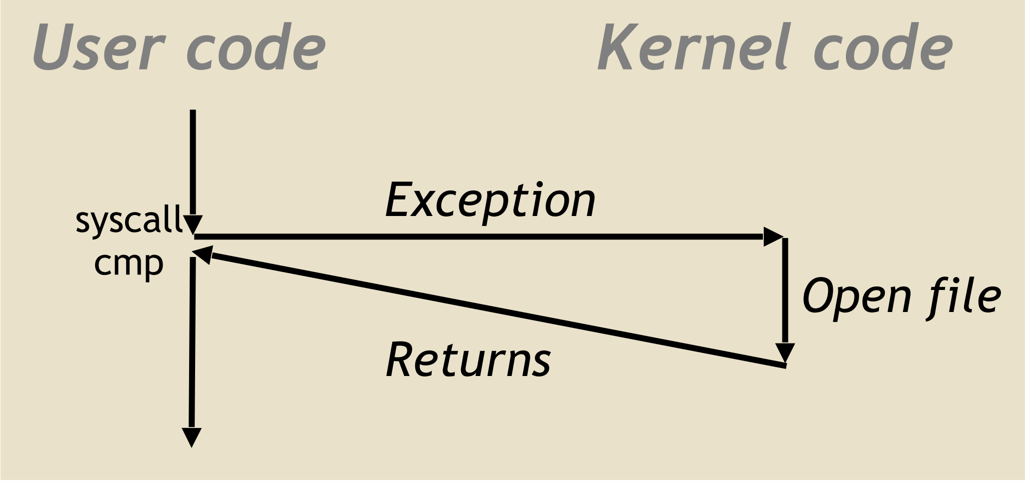
Synchronous Exceptions

- **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

System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

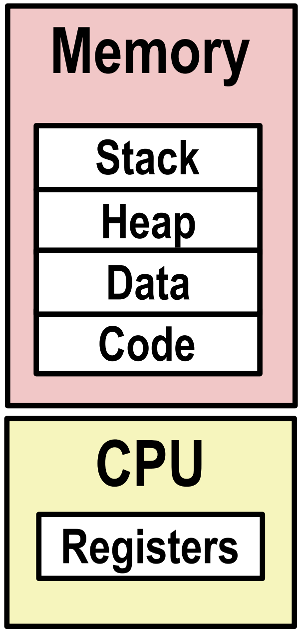
```
00000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%rax  # open is syscall #2
e5d7e:   0f 05               syscall         # Return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001, %rax
...
e5dfa:   c3                  retq
```



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative errno

+ 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

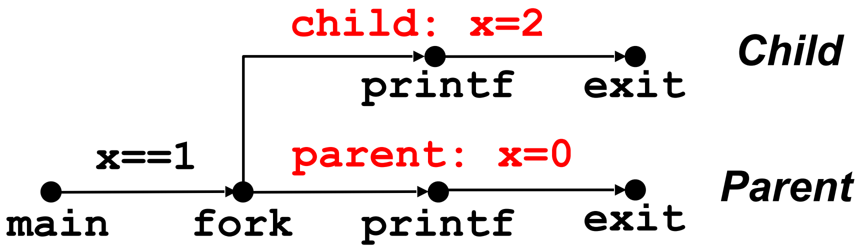
- **From a programmer's perspective, we can think of a process as being in one of three states**
- **Running**
  - Process is either executing, or waiting to be executed and will eventually be scheduled (i.e., chosen to execute) by the kernel
- **Stopped**
  - Process execution is suspended and will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

+ 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

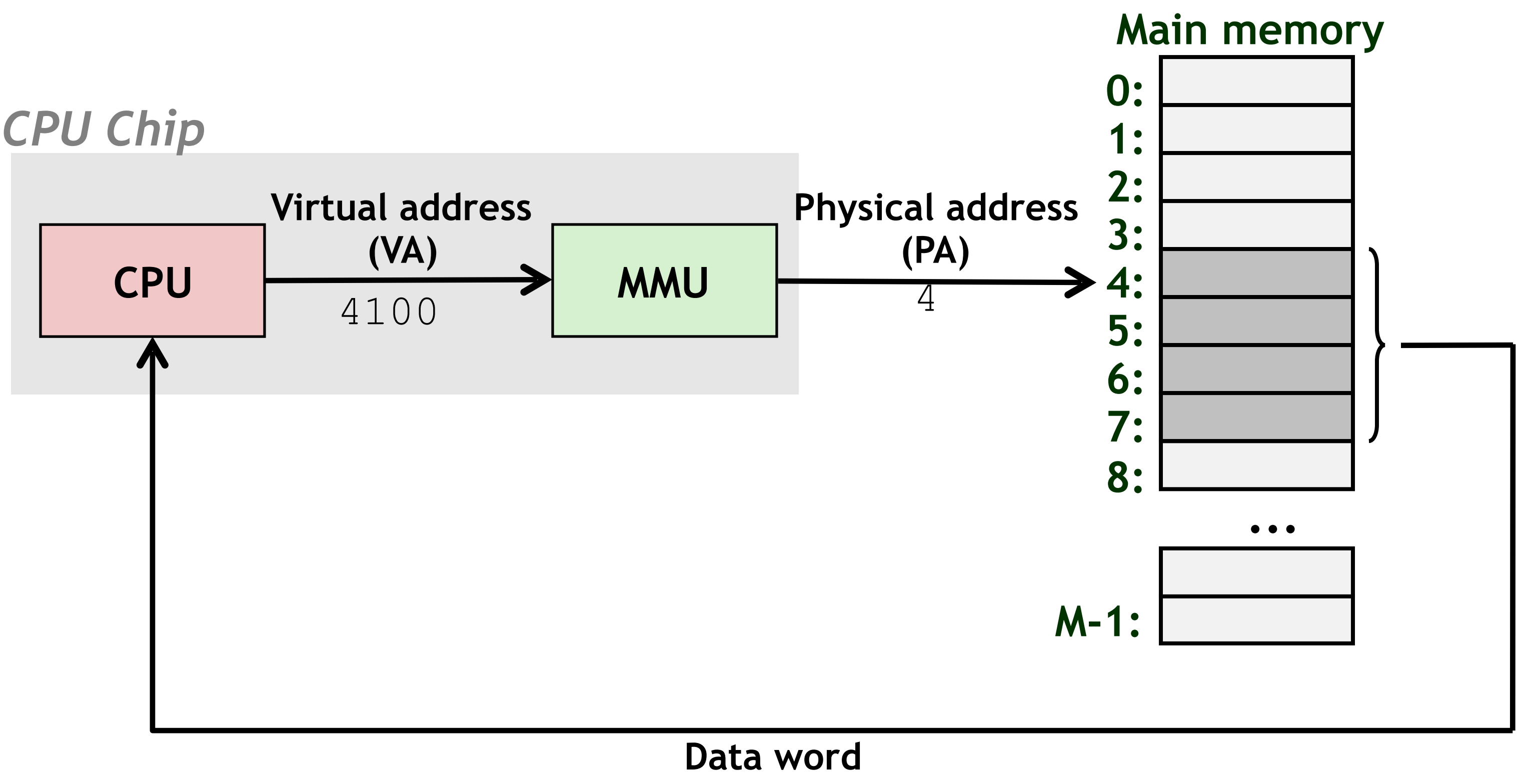
+ Process Graph Example

```
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 Addressing

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

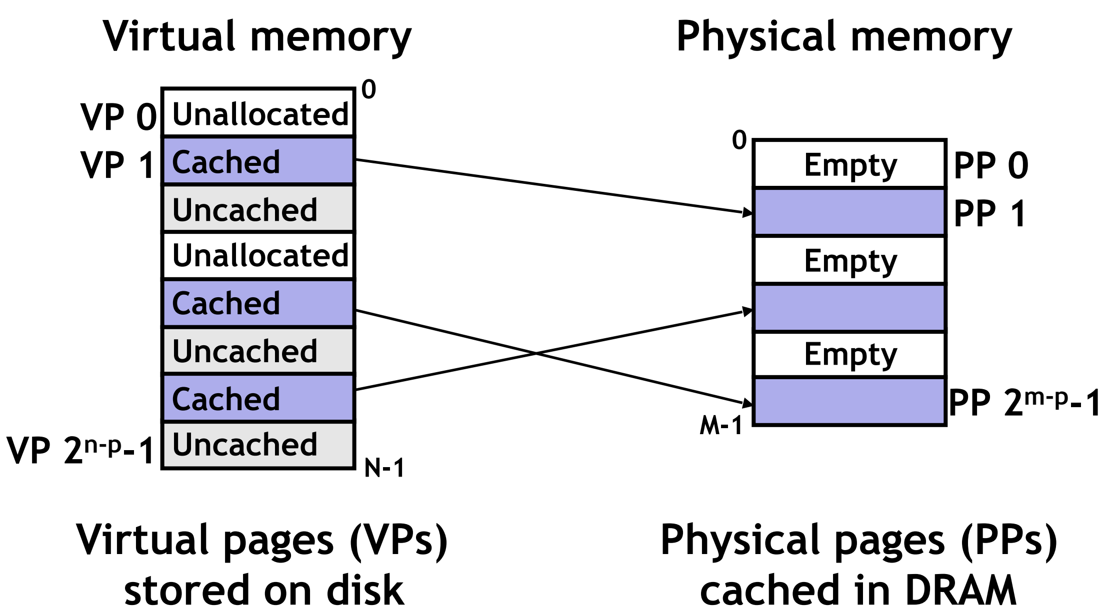


+ Why Virtual Memory (VM)?

- **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*



Dynamic Allocation

+ Dynamic Memory Allocation

- **Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free***
- **Types of allocators**
  - *Explicit* allocator: application allocates and frees space
    - E.g., `malloc` and `free` in C
  - *Implicit* allocator: application allocates, but does not free space
    - E.g. garbage collection in Java, ML, and Lisp

+ 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 Goal: Throughput

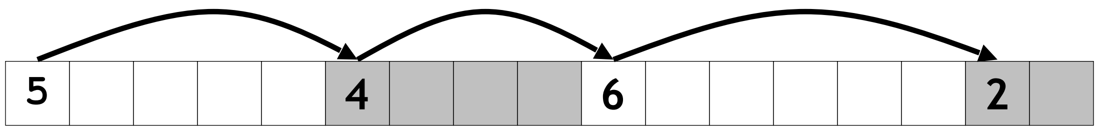
- **Goal: Maximize throughput:**
  - Number of completed requests per unit time
  - Example:
    - 5,000 `malloc` calls and 5,000 `free` calls in 10 seconds
    - Throughput is 1,000 operations/second

+ Performance Goal: Peak Memory Utilization

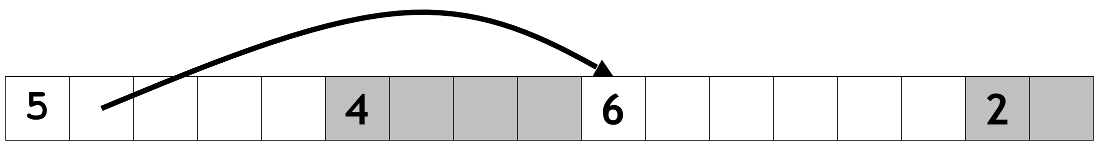
- ***Aggregate payload / Current heap size = Utilization***
  - Utilization is the sum of currently allocated payloads divided by the current total heap size.
- **Goal: Increase utilization (by reducing fragmentation)**
  - internal fragmentation
  - external fragmentation

Free Lists: Keeping Track of Free Blocks

- **Method 1: Implicit list using length—links all blocks**



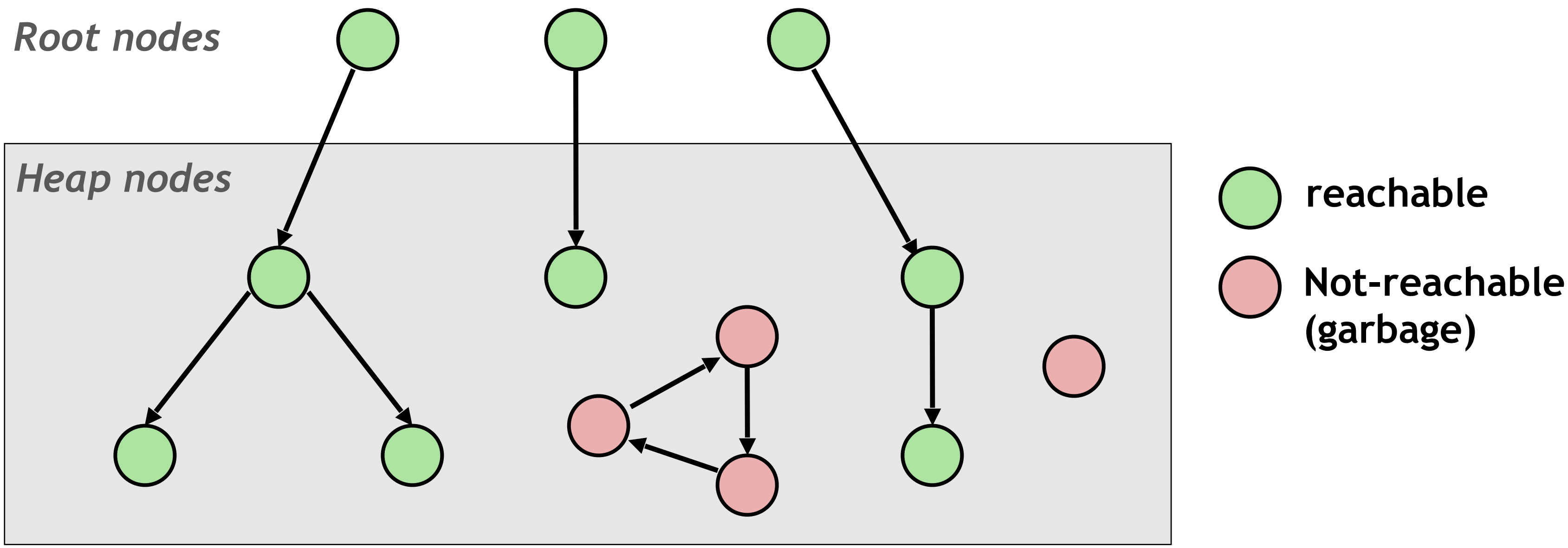
- **Method 2: Explicit list among the free blocks using pointers**



- **Method 3: Segregated free list**
  - Different free lists for different size classes

+ Memory as a Graph

- **We view memory as a directed graph**
  - Each block is a node in the graph, each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called root nodes (e.g. registers, locations on the stack, global variables)



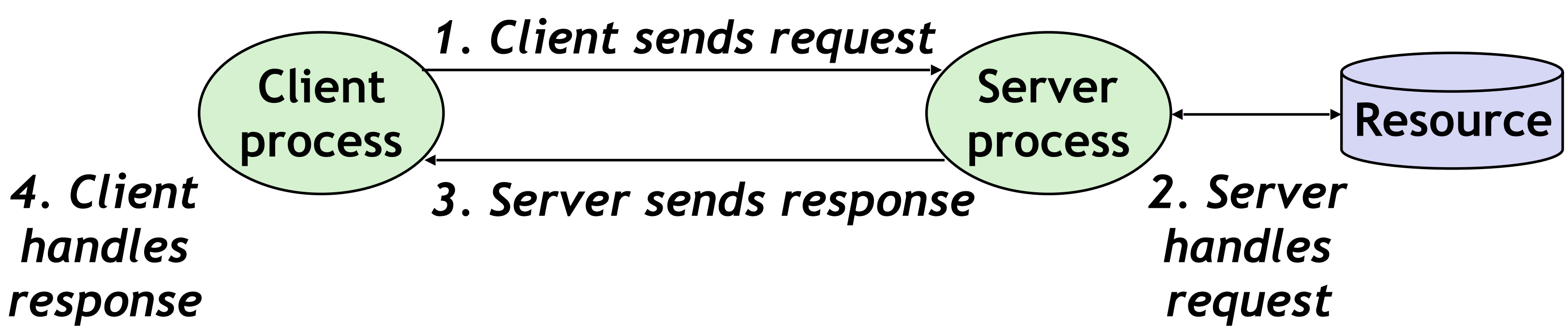
A node (block) is *reachable* if there is a path from any root to that node.

Non-reachable nodes are *garbage* (cannot be needed by the application)

Network Programming

A Client-Server Transaction

- **Many network applications are based on the client-server model:**
  - A server *process* and one or more client processes
  - Server manages some *resource*
  - Server provides service by manipulating resource for clients
  - Server activated by *request* from client



Note: clients and servers are processes running on hosts (can be the same or different hosts)

+ Computer Networks

- **A network is a group of connected systems that are able to communicate in order to exchange data.**
- **There are many kinds of networks, some examples..**
  - *LAN* (Local Area Network) spans a building or campus
    - *Ethernet* is a prominent example
  - *WAN* (Wide Area Network) spans country or world
    - Typically high-speed *point-to-point telecom lines*
- **Network devices that originate, route and terminate data are called '*nodes*'.**
  - Nodes or '*hosts*' can be personal computers, phones, servers as well as special networking hardware.

+ Computer Networks *con't*

- **Two devices can be said to be '*networked*' when one device is able to exchange information with the other.**

- **An '*internetwork'* (internet) is a connected set of networks**
  - The Global IP Internet (uppercase "I") is the most famous example of an internet (lowercase "i")

- **A '*router*' is an networking device that forwards data between networks in an internet.**

- **A '*link*' is the means of connecting one location to another for the purpose of transmitting and receiving data across networks.**
  - phone lines, fiberoptic cables, smoke signals, etc…

+ Sockets

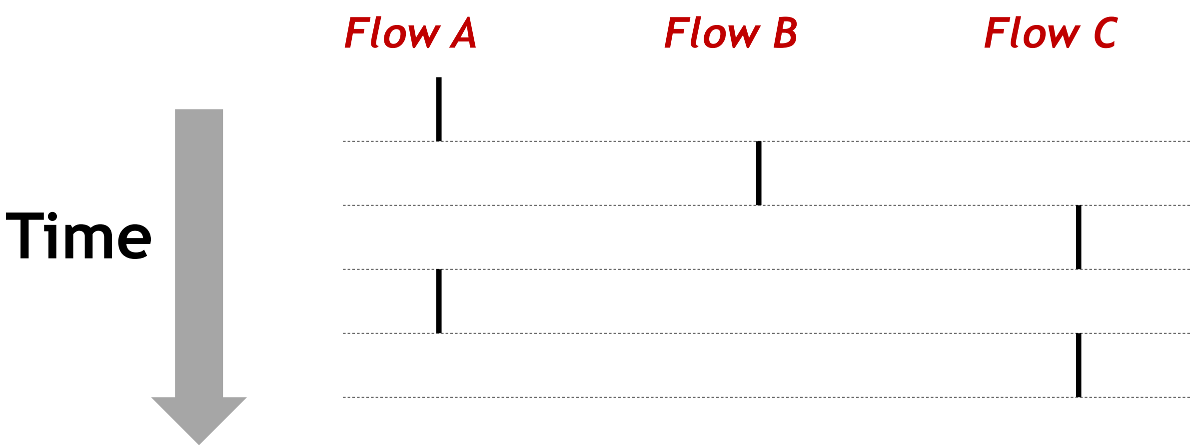
- **What is a socket?**
  - To the kernel, a socket is an endpoint of communication
  - To an application, a socket is a file descriptor that lets the application read/write from/to the network
    - All Unix I/O devices, including networks, are modeled as files
- **Clients and servers communicate with each other by reading from and writing to socket descriptors**

- **The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors**

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
  - *Deadlock*: improper resource allocation prevents forward progress
  - *Livelock / Starvation / Fairness*: external events and/or system scheduling decisions can prevent sub-task progress

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

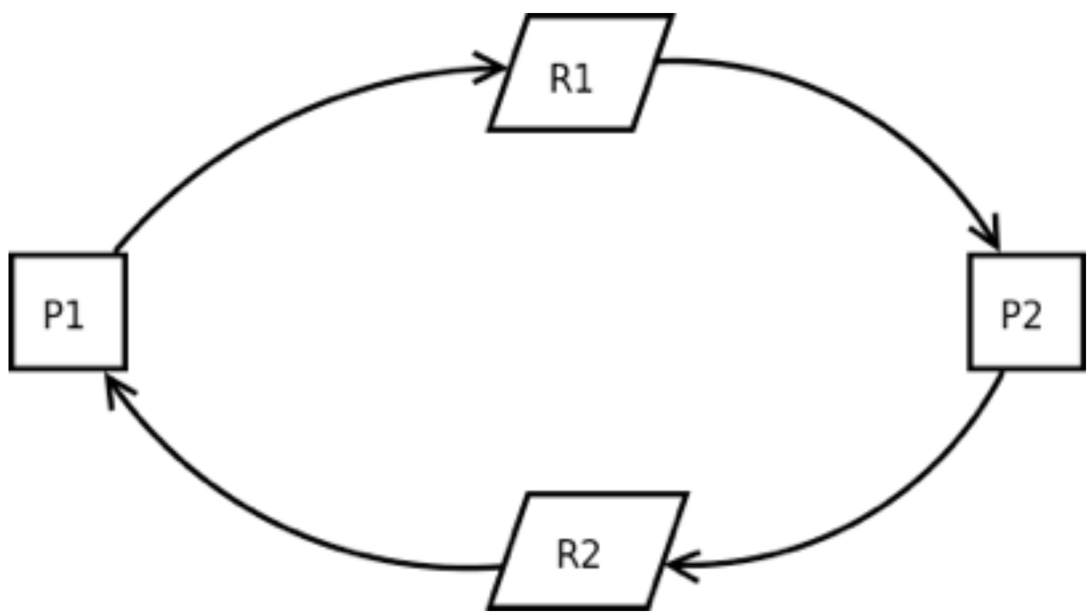
- **Shared variables are sometimes useful but they introduce the possibility of *synchronization* errors.**
  - Like the one we saw last time
- **How do we prevent such things?**
  - We need to make sure that only one thread is mutating shared variables at a time.
  - This is known as *mutual exclusion*
- **Moreover, we must protect *critical sections*.**

+ 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…**

+ Deadlock

- Both processes need resources to continue execution.
- P1 requires additional resource R1 and is in possession of resource R2
- P2 requires additional resource R2 and is in possession of R1; neither process can continue.



Thread Safety

- **Functions called from a thread must be *thread-safe***
- **Def: A function is thread-safe iff it will always produce correct results when called repeatedly from multiple concurrent threads**
- **Classes of thread-unsafe functions:**
  - Class 1: Functions that do not protect shared variables
  - Class 2: Functions that keep state across multiple invocations
  - Class 3: Functions that return a pointer to a static variable
  - Class 4: Functions that call thread-unsafe functions ☺