Final Review

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Final logistics

- 100 minutes (half an hour longer than quiz1&2)
  - Cover all materials
  - More emphasis on the second half of class (70%)
- Closed book
  - except for one double-sided cheat sheet
  - No electronic devices
- Read all questions, do the easier ones first.

Disclaimer: this review is not complete.

Not all exam materials are covered by this review!

What we've learnt (first half)

1. C language
   – pointers, bitwise operations
   – Compilation, linking
2. Basic program execution
   – Digital representation of numbers and characters
   – CPU state vs. memory, basic x86 instructions
   – Buffer overflow

What we've learnt (second half)

3. Dynamic Memory Allocation
4. Advanced program execution
   - virtual memory
   - caching
   - Multi-processing
5. Multi-threading

Topic #1
C programming

Global vs. Local vs. Heap Variable

- Know the whereabouts of variables, when they are allocated/deallocated
- Variables are not automatically initialized upon declaration

```
void add(int x) {
  x++;
}

void main() {
  int x = 0;
  add(x);
  printf("x is %d\n", x);
}
```

What's the output?

Answer: 0

Global vs. Local vs. Heap Variable

- Know the whereabouts of variables, when they are allocated/deallocated
- Variables are not automatically initialized upon declaration

```
int add(int x) {
  x++;
  return x;
}

void main() {
  int x = 0;
  x = add(x);
  printf(“x is %d\n”, x);
}
```

What’s the output?

Answer: 1

Global vs. Local vs. Heap Variable

- Know the whereabouts of variables, when they are allocated/deallocated
- Variables are not automatically initialized upon declaration

```
int add(int x) {
  x++;
  return x;
}

void main() {
  int x = 0;
  x = add(x);
  printf("x is %d\n", x);
}
```

What's the output?

Answer: Could be any number

Pointers

- Pointers are addresses to variables
- You must be aware of whether the variable being pointed to has been allocated or not and where

```
void add(int *x) {
  (*x) = (*x) + 1;
}

void main() {
  int y = 0;
  int *x = &y;
  add(x);
  printf("x is %d\n", *x);
}
```

What's the output?

Answer: 1

Pointers

- Pointers are addresses to variables
- You must be aware of whether the variable being pointed to has been allocated or not, and where

```
void add(int *x) {
  (*x) = (*x) + 1;
}

void main() {
  int y = 0;
  int *x = &y;
  add(x);
  printf(“x is %d\n”, *x);
}
```

What’s the output?

Answer: Likely segmentation fault

#1.2 C Programming

- Pointers are ddresses to variables
- You must be aware of whether the variable being pointed to has been allocated or not, and where

```
int *
sum(int x, int y) {
   int z = x + y;
   return &z;
}

void main() {
   int *r1 = sum(1,1);
   int *r2 = sum(*r1, 1);
   printf("%d\n", *r2);
}
```

What's the output?

Answer: likely garbage

Pointers and arrays

- Arrays store a set of identically typed elements contiguously

```
void main() {
    int nums[5] = {1, 2, 3, 4, 5};
    int *p;
    p = nums + 2;  // equivalent to p = &nums[2];
    p++;
    printf(“%d\n”, *p);
}
```

What’s the output?

Answer: 4

Little vs. Big Endian

```
void main() {
  int x = 1<<31;   // equivalent to x = 0x80000000;
  char *y;
  y = (char *)&x;
  for (int i = 0; i < 4; i++) {
     printf("%d ", y[i]);
  }
}
```

y[3]:		0x80	lower addr
y[2]:		0x00	
y[1]:		0x00	
y[0]:	x:	0x00	

What's the output?

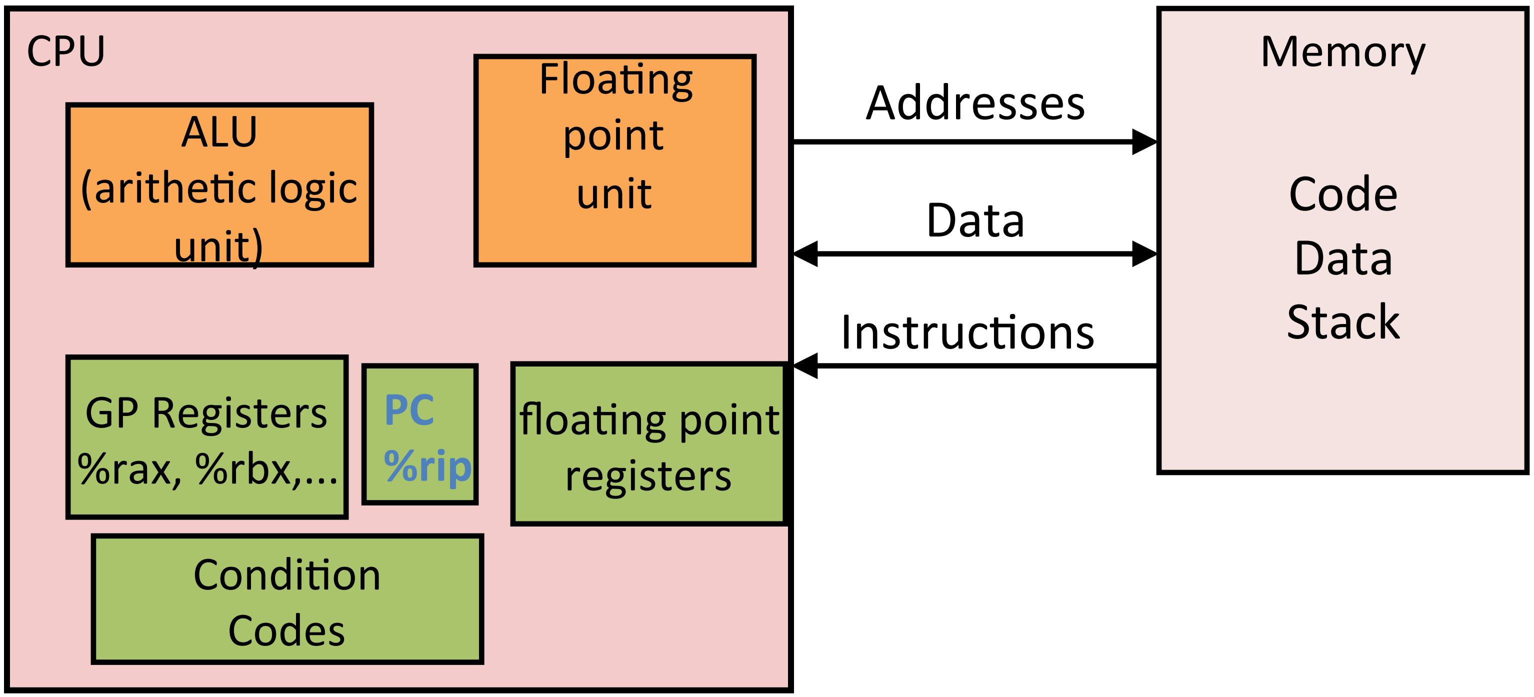
Answer: 0 0 0 -128
(little Endian)

C: Other Concepts

- ASCII characters
- C string
  - Null-terminated ASCII character array
- Use malloc appropriately
  - allocate the right size
  - free allocated memory to avoid memory leak

Topic #2
Basic Program Execution

Basic Program Execution



Machine instructions: mov

1. mov instructions

general memory addressing mode:
D(Rb, Ri, S): val(Rb) + S*val(Ri) +D

S: 1, 2, 4, or 8

	Source	Dest	Source, Dest
movq	*Imm*	*Reg*	`movq $0x4,%rax`
		Mem	`movq $0x4,(%rax)`
	Reg	*Reg*	`movq %rax,%rdx`
		Mem	`movq %rax, 16(%rbx, %rdx, 8)`
	Mem	*Reg*	`movq (%rax),%rdx`

Machine instructions

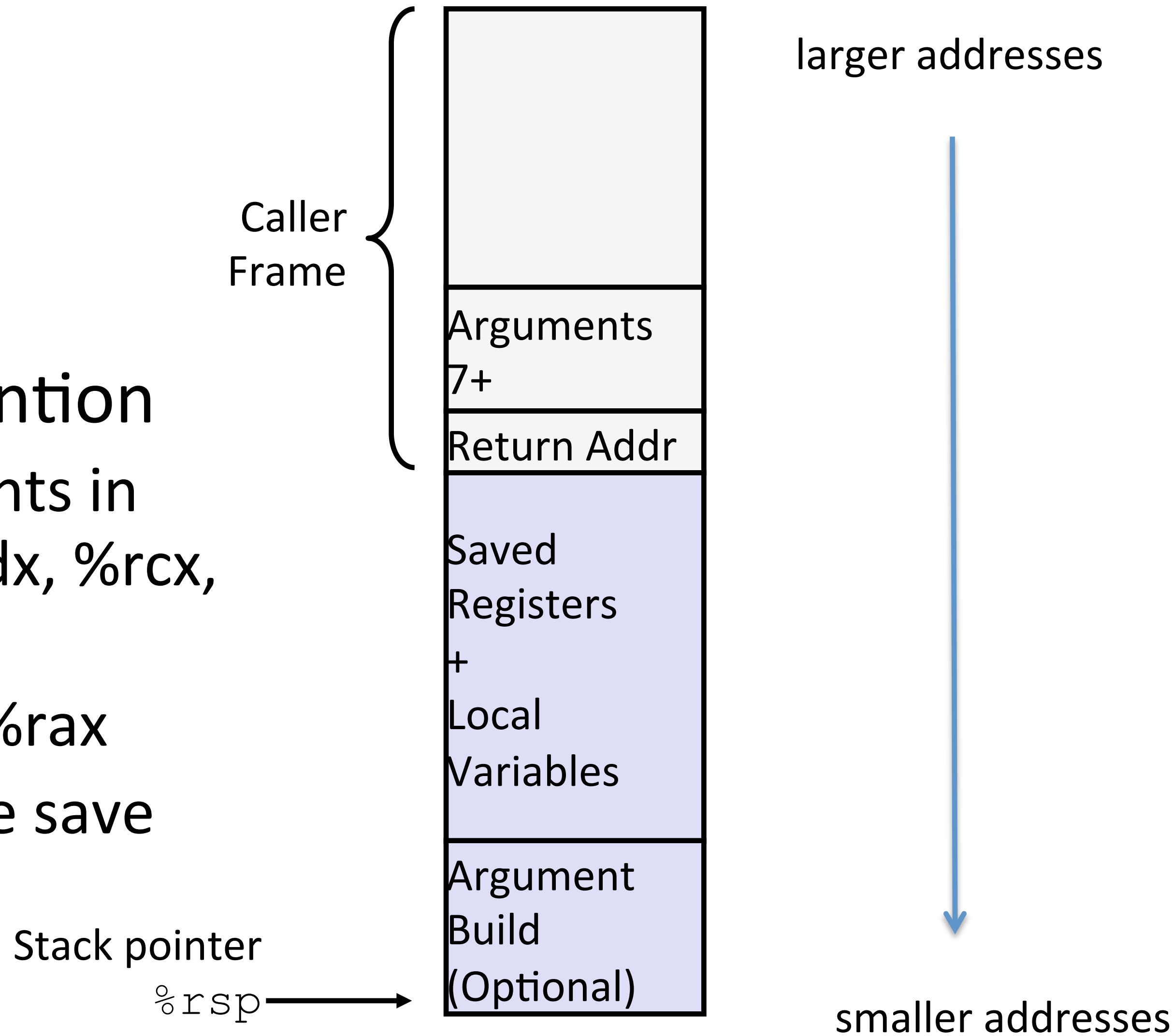
- Arithmetic operations
  - add %eax, %ebx
  - sub, mul
- The lea instruction
  - lea 0x1(%rax, %rbx, 2), %rdx
- Bitwise-operations:
  - shl/shr, sal/saq, and, or, xor

Control flow

- Normal control flow is linear
  - load instruction stored at address %rip
  - execute it
  - %rip = %rip + (length of instruction)
- Non-linear Control flow
  - combination of two types of instructions
    - instructions that set conditional codes, CF, ZF, SF, OF
    - jmp instructions that may or may not jump depending on condition codes
  - condition codes can be set
    - implicitly: add, sub ..
    - explicitly: cmp, test, ...

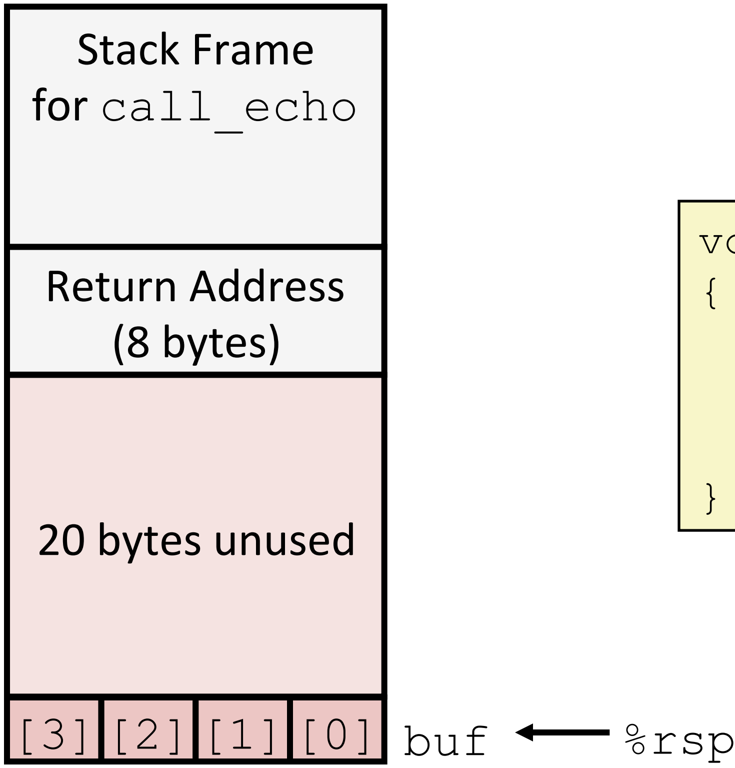
Procedure execution

- `call, ret`
- `push, pop`
  - %rsp
- C calling convention
  - first 6 arguments in %rdi, %rsi, %rdx, %rcx, %r8, %r9
  - return value: %rax
  - caller vs. callee save registers



Buffer Overflow

Before call to gets




```
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

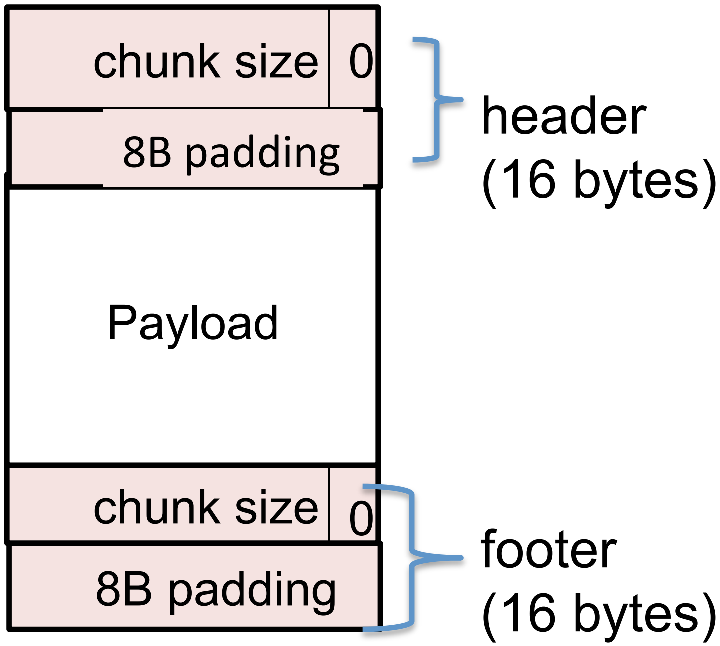
Topic #3
Dynamic Memory Allocation

Dynamic memory allocation

- How to implement malloc/free?
- Goal: high throughput and high utilization
- Design questions:
  - how to keep track of free blocks
  - which free blocks to allocate?
  - free is only given a pointer, how to know its block size?

Dynamic memory allocation

- implicit list
  - one (implicit) list containing all free and non-free blocks
- explicit free list
  - one explicit linked list containing all free blocks
- segregated free list
  - multiple explicitly linked lists for free blocks,
  - each links corresponds to a different size class




```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;

bool get_status(header *h) {
   return h->size_and_status & 0x1L;
}
size_t get_chunksize(header *h) {
   return h->size_and_status& ~(0x1L);
}
```

Question: given pointer p of type void * pointing to the payload, how to get a pointer to the current, next, previous block?

curr = (header *)((char *) p – sizeof(header));

next = (header *)((char *)p + sizeof(header) + get_chunksize(curr));

footer = (header *)((char *)p – 2*sizeof(header));

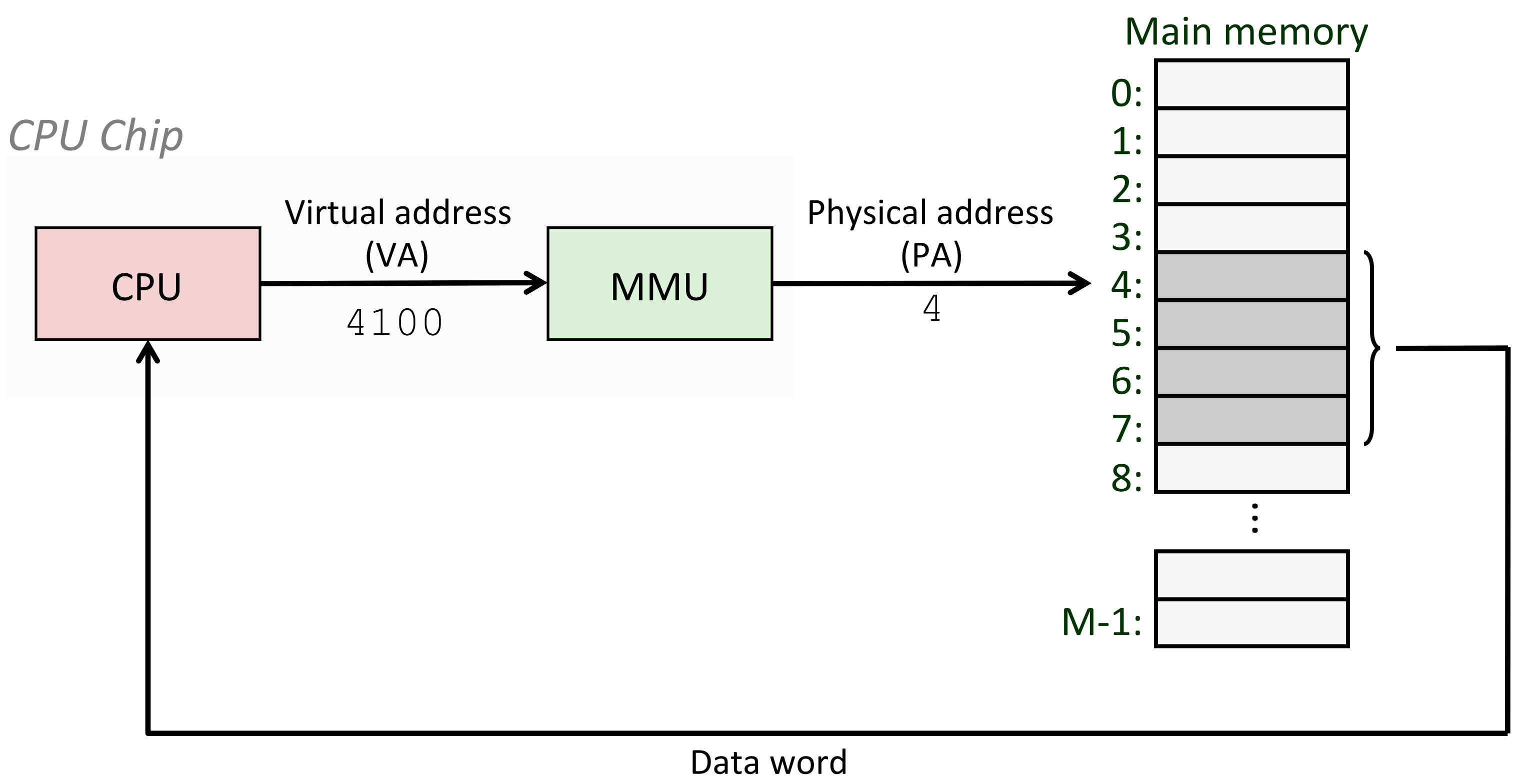
prev = (header *)((char *)p – 3*sizeof(header)-get_chunksize(footer));

Topic #4
Advanced topics on program execution

VM, Caching, Multiprocessing

Virtual memory

- User program access virtual address
- 32-bit address ➔address range `[0x00000000, 0xffffffff]`

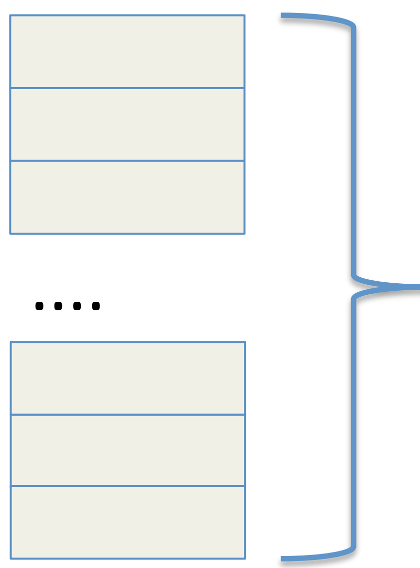


VM: one-level page table

- Example:
  - 8-bit virtual and physical addresses
  - 16-byte page size

How many pages in the 8-bit address space?

Answer: 2^8/16 =2^4 = 16 pages



page table is an array of PTEs.

How many PTEs needed to address all pages in address space?

Answer: 16 PTEs

VM: one-level page table

- Example:
  - 8-bit virtual and physical addresses
  - 16-byte page size

VA:

`0x11010010`

What's the PA?

Answer: page fault

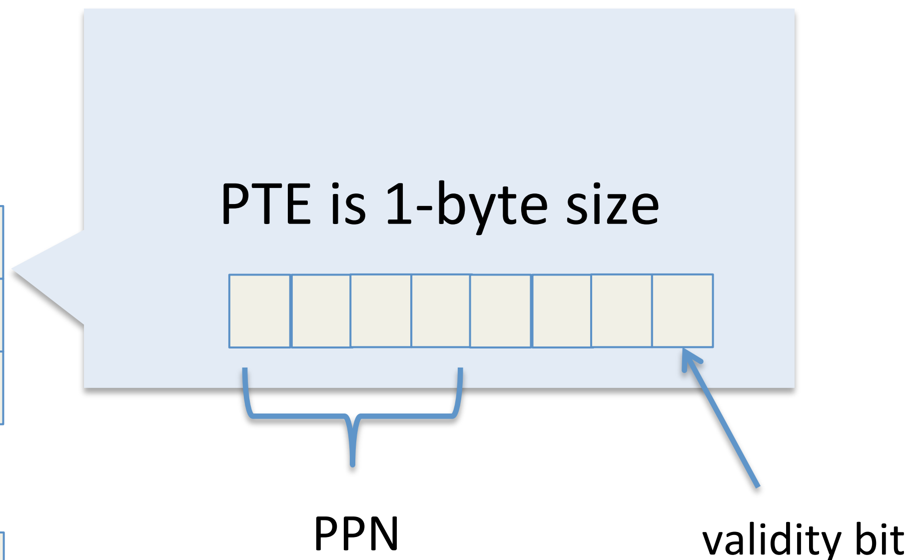
VA:

`0x11100010`

What's the PA?

Answer: 0xB2

ptable[15]:	0xA1
ptable[14]:	0xB1
ptable[13]:	0xC0
....	
ptable[2]:	0xD0
ptable[1]:	0xF1
ptable[0]:	0xE0



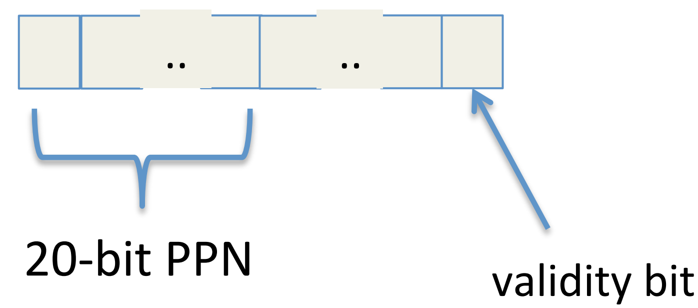
VM: Multi-level page table

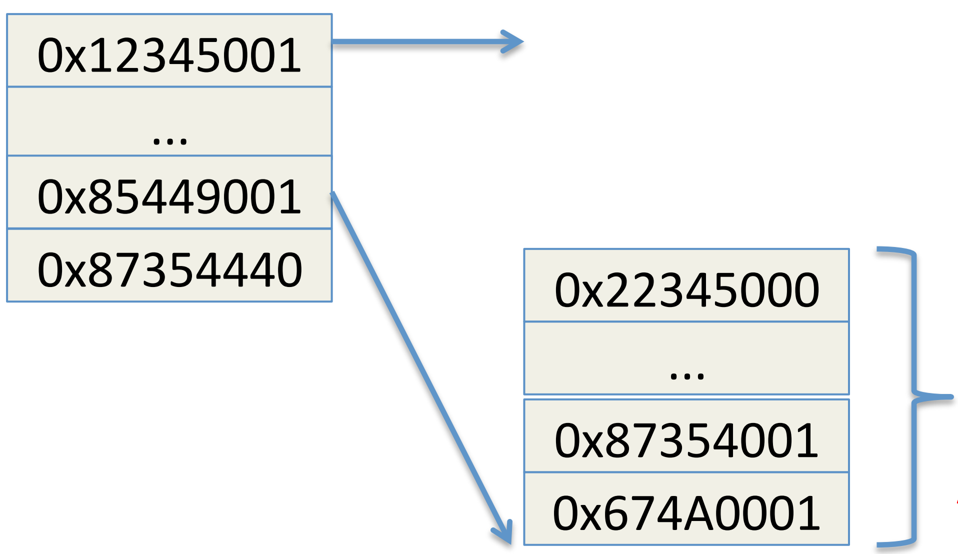
- Example:
  - 32-bit virtual and physical addresses
  - 4KB page size

How many pages in the 32-bit address space?

Answer: 2^32/4KB =2^20 pages

PTE is 4-byte size



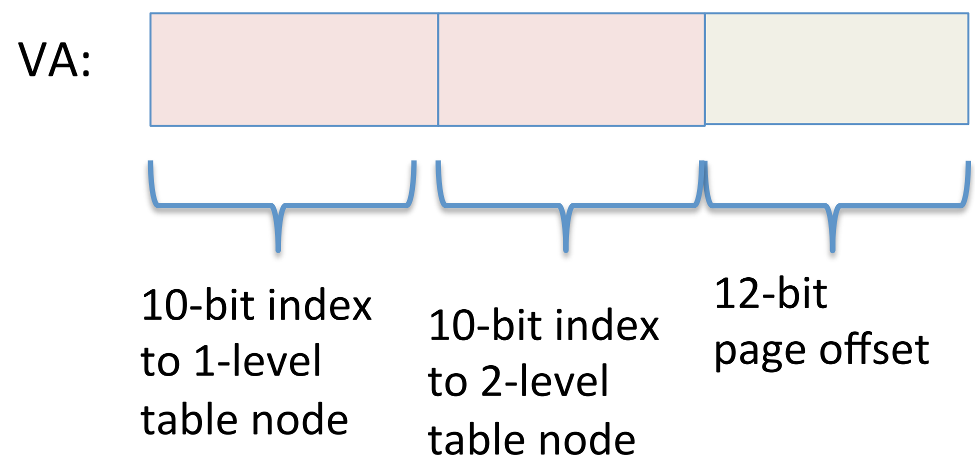


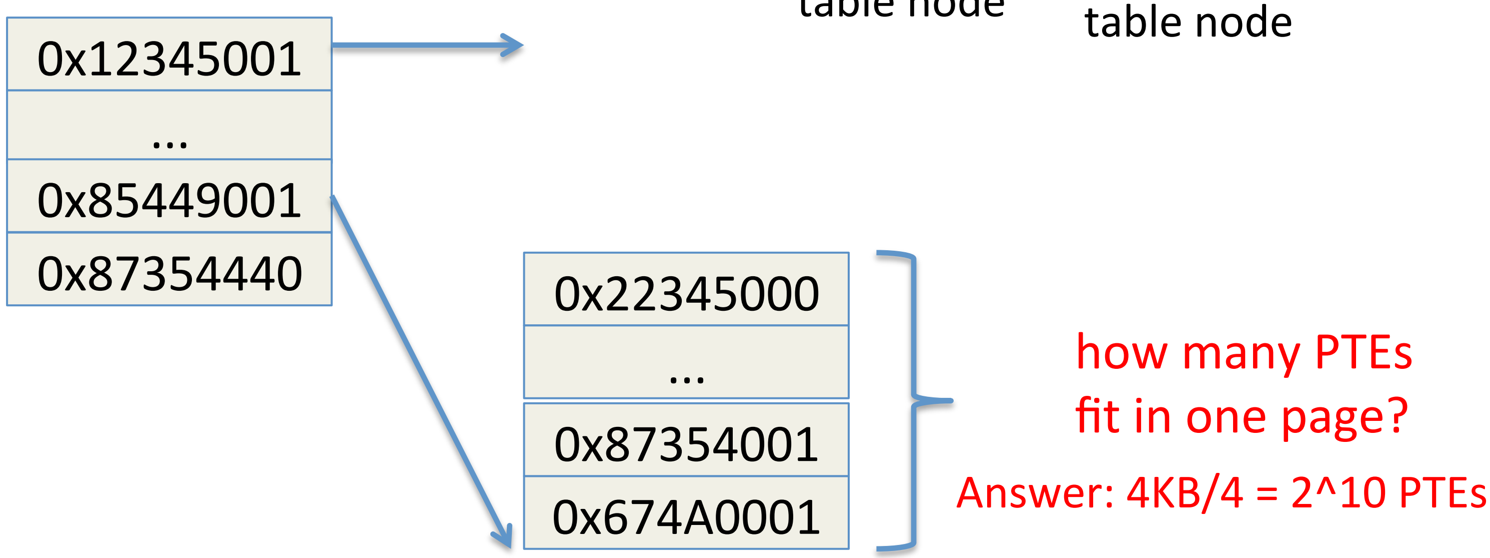
how many PTEs fit in one page?

Answer: 4KB/4 = 2^10 PTEs

VM: Multi-level page table

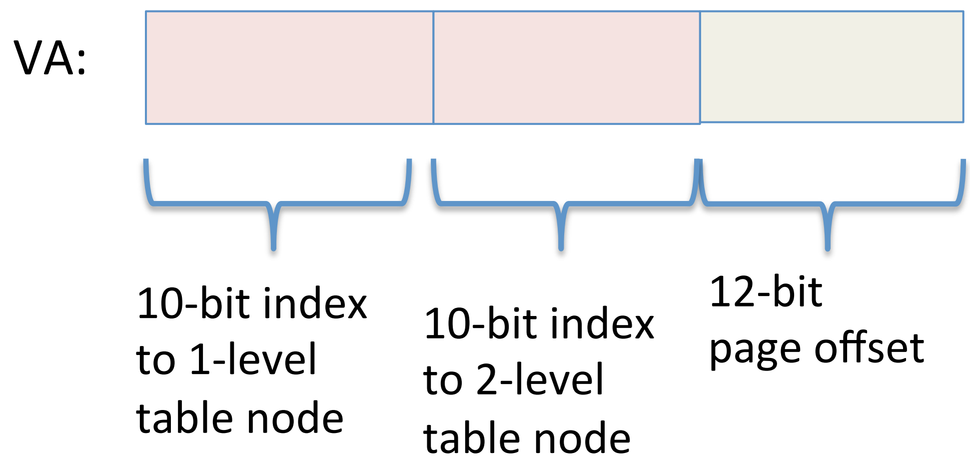
- Example:
  - 32-bit virtual and physical addresses
  - 4KB page size

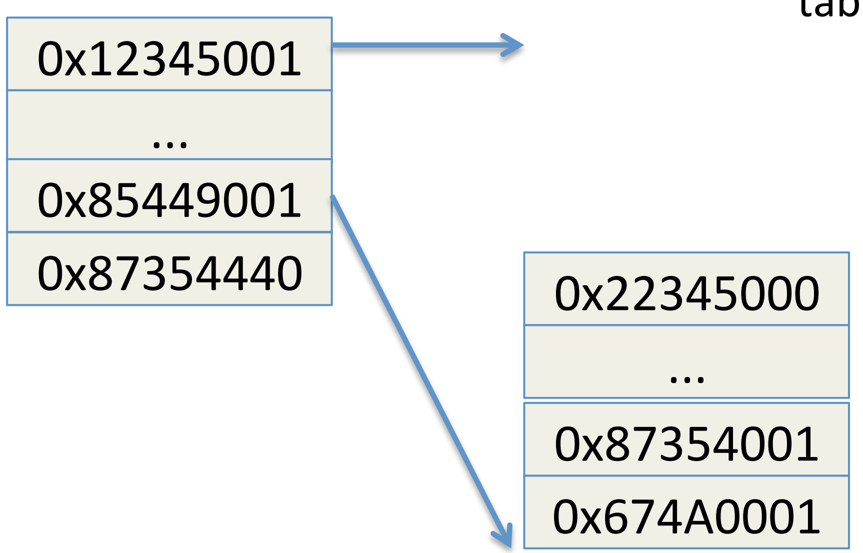




VM: Multi-level page table

- Example:
  - 32-bit virtual and physical addresses
  - 4KB page size



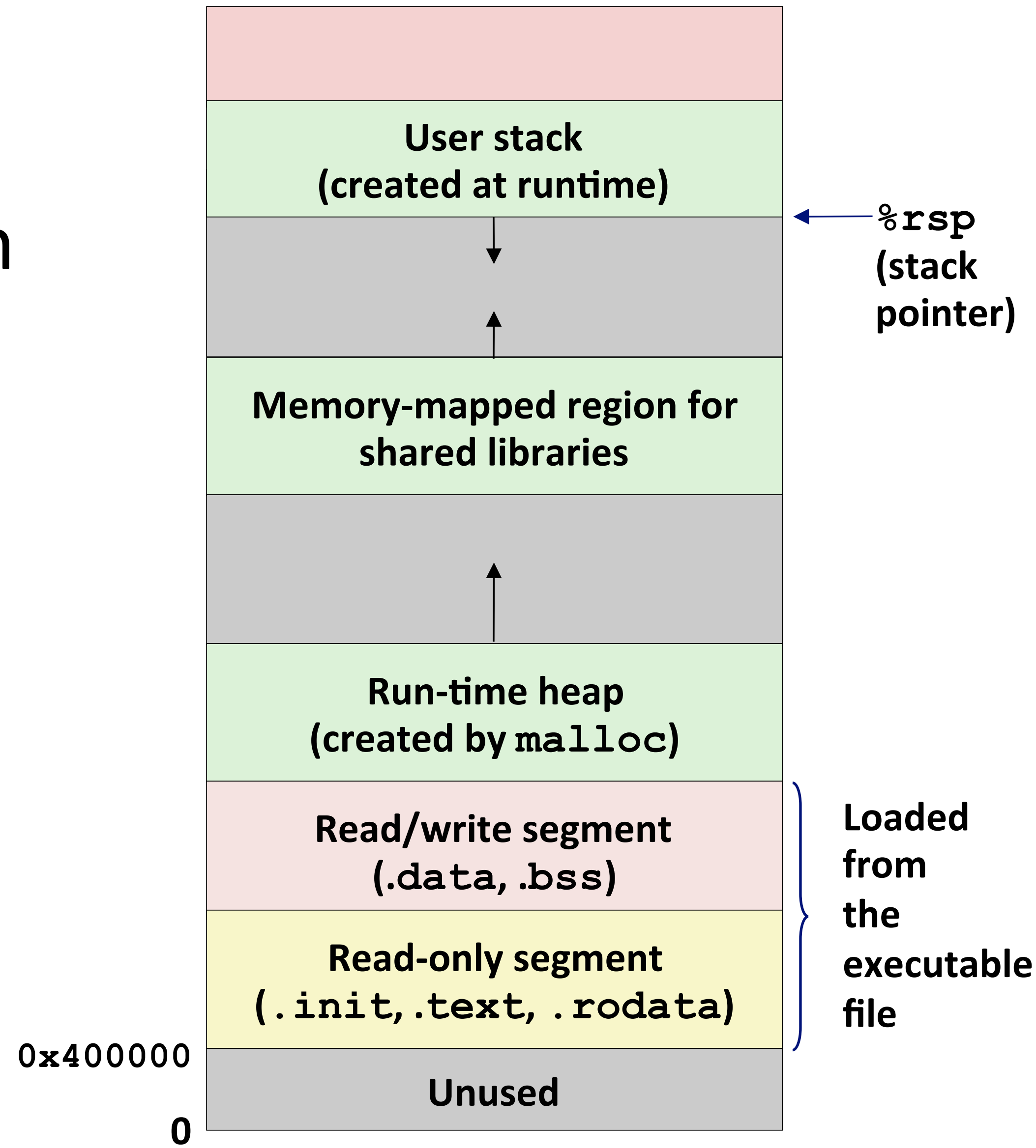


VA: 0x00401678
What is PA?
Answer:674A0678

VA: 0x00001678
What is PA?
Answer: page fault

Address space

- Each running program has its own page table and address space



OS and user-level processes

- OS: a layer of software between app and h/w
  - hide h/w details
  - manage resource sharing among apps
- H/w primitive: privileged vs. unprivileged execution
  - exception (e.g. page fault)
  - traps (used for syscall)
  - interrupt (e.g. timer interrupt)

invoking kernel functions: syscalls

- h/w instruction, syscall
  - open, close, read, write
  - futex, fork, clone
  - man 2 fork

OS abstraction: Multi-processing

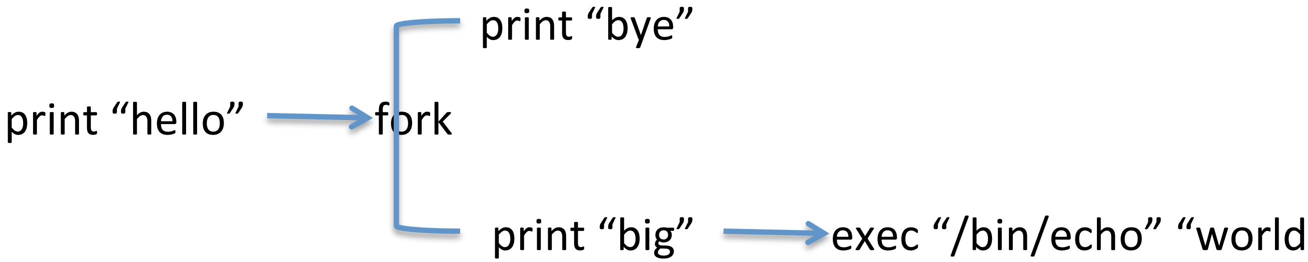
- Process: an instance of a running program
- Managed by OS, each process has
  - its own virtual address space
  - saved execution context
  - process id
  - ....

fork and exec

```
void main() {
    printf("hello\n");
    if (fork() == 0) {
      printf("big\n");
      exec(“/bin/echo”, “world”);
      printf(“lovely\n”);
      }
    }
    printf("Bye\n");

}
```

- What are potential interleavings?



hello	hello	hello
big	big	bye
bye	world	big
world	bye	world

forked processes have separate address space

```
int global = 1;
void main() {
    pid_t pid = fork();
    if (pid == 0) {
      global = 2;
      printf("child global=%d\n", global);
    } else {
      waitpid(pid,...)
      printf("parent global=%d\n", global);
    }
}
```

- What are possible outputs?

  child global=2
  parent global=1

Topic #5
Multi-threaded programming

Concurrent programming

- A single process can have multiple threads
  - each thread has its own control flow & stack
  - all threads share the same address space
- Multi-threaded programs need synchronization
- Synchronization problems:
  - races
  - deadlock

Races

- Examples:
  - modifying shared counters
  - modifying shared linked list, hash table etc.
- Caused by arbitrary interleaving of execution among different threads

Thread-1 (x++)

```
read x (from
memory) into %eax
```

```
add $1, %eax
```

```
write %eax to x (in memory)
```

Thread-2 (x++)

```
read x into %eax
```

```
add $1, %eax
```

```
write %eax to x
```

Races

```
node *head;
list_insert(int x) {
   L1: node *n = malloc ...
   L2: n->val = x;
   L3: n->next = head;
   L4: head =n;
}
```

what can go wrong if two threads insert at the same time?

Thread-1: list_insert(1)	Thread-2: list_insert(2)
L1 L2	L1 L2
L3	
	L3
	L4
L4	

Mutexes

- Protect “critical section”

Big lock implementation

```
int acc[100];
pthread_mutex_t mu;
void transfer(int x, int y){
  pthread_mutex_lock(&mu);
  acc[x] -=10;
  acc[y] += 10;
  pthread_mutex_unlock(&mu);
}
```

Fine-grained lock

```
typedef struct {
  int balance;
  pthread_mutex_t mu;
}account_t;

account_t acc[100];

void transfer(int x, int y) {
pthread_mutex_lock(&acc[x].mu);
pthread_mutex_lock(&acc[y].mu);
acc[x].bal -= 10;
acc[y].bal += 10;
pthread_mutex_unlock(&acc[x].mu);
pthread_mutex_unlock(&acc[y].mu);
}
```

Conditional variables

- lets a thread wait for some condition to become true
- Remember the pattern for using conditional variables

Thread-1

```
mutex_lock(&m)

while (condition != true)
    cond_wait(&c, &m);

//condition is true
modify shared state

mutex_unlock(&m)
```

Thread-2

```
mutex_lock(&m);

condition = true;
cond_signal(&c);
//or cond_broadcast(&c)

mutex_unlock(&m);
```

H/W Atomic instructions

- Basic spinlock implementation

```
spin_lock(int *m)
{
    while (xchg(m, 1)!= 0);
}

spin_unlock(int *m)
{
    xchg(m, 0);
}
```