

COM SCI 33
Glenn Reinman
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Bits & Bit Operators

- Byte - sequence of 8 bits (encodings: 8 digits in binary, 0-255 in decimal, 00-FF in hex)
 - Encodings determine how meaningless bits are interpreted
 - Binary - prepended by 0b, hexadecimal - prepended by 0x
- *Bit pattern operators*: ~ (unary operator),
 - ~ (**unary** operator/complement): given a bit pattern, flips all bits of a bit pattern
 - & (intersection/**AND**): given two bit patterns, output bit is 1 iff both input bits are 1
 - | (union/**OR**): given two bit patterns, output bit is 1 if at least one input bit is 1
 - ^ (exclusive-or/**XOR**): given two bit patterns, output bit is 1 iff only one input bit is 1
 - ~ (unary/complement), & (intersection), | (union), ^ (exclusive-or) bitwise operators implemented in C (treat arguments as bit vectors, applied bit-by-bit)
 - Note: AND, OR, XOR are commutative
 - Vs logical operators &&, e.g.
- *Shift operators*:
 - **Left shift** (<<) vs **right shift** (>>) - shift bit vector x to left/right by y positions (i.e. begin at x_0 -> begin at x_3/x_(-3))
 - Left shift - fills with 0s on right
 - Right (**logical**) - fill with 0s on left
 - Only relevant for C, unsigned
 - Right (**arithmetic**) - replicate most significant bit (bit position-wise) on left
 - Preserves negative sign, in the case of signed integers
 - Shifting left/right overwrites bits on left/right
 - Undefined - negative shift amounts, shift amounts > word length
- Instructions stored in [readable/read-only] addresses in memory [stored in bytes], referenced by program calls
 - Size of an instruction may vary based on contents
 - Data can be placed in various places, depending on the compiler - read-only memory, dynamically allocated memory, registers (e.g.)

Computers

- **[Instruction Set] Architecture (ISA)** - interface between hardware and software
 - ISA understands instructions, registers, condition codes of the hardware
- **Microarchitecture** - implementation of the architecture
- Programmers typically deal with 2 parts of a computer - **CPU** and **memory**
 - Parts of the **CPU**
 - **Programmer counter (PC)** - contains address of next instruction for computer to execute ("RIP" on Intel)
 - **Register file** - contains heavily-used program data
 - **Condition codes** - store status information about recent [arithmetic/logical] operations (used for conditional branching)
 - **Cache** - smaller memory container located directly on the CPU, allowing for faster, less expensive memory accessing
 - **Memory** - contains code and user data
 - Also has an *internal stack* to support procedures
 - Stored in the form of a byte-addressable array
 - CPU pulls data and instructions from memory; accesses memory using addresses
 - GPUs usually have simpler core designs
- Transferring memory: memory transferred in contiguous fixed-size chunks
 - **Blocks** used for transferring between cache, DRAM
 - **Pages** used for transferring between disk, DRAM (generally larger than blocks)
 - Computer minimizes the number of blocks, pages used for transferring information
 - Primitive types are best optimized by transferring in single blocks/pages, rather than being split across multiple
- *Virtual memory* - the "memory" that programs see is not the same as the physical memory of the system (DRAM)
 - When programs allocate [virtual] memory, the addresses they use do not necessarily correspond to addresses on physical memory
 - A *memory management unit* (MMU) on the CPU translates from logical addresses (in virtual memory) to physical addresses (on the hardware itself)

Integers

- Integer encodings:
 - **Unsigned:** every bit represents a power of 2
 - $B2U(x)$ [bit to unsigned] = $\sum(x_i * 2^i)$, $0 < i < w-1$ [w = num digits - 1]
 - An unsigned integer represented by a w -digit bit sequence has a range of 0 [$UMin$] < $B2U(x)$ < $2^w - 1$ [$UMax$]
 - Used for representing nonnegative values - can fail
 - **Two's complement** (signed integers in ANSI C):
 - $T2U(x) = (x_{(w-1)} * -2^{(w-1)}) + \sum(x_i * 2^i)$, $0 < i < w-2$
 - Most significant digit indicates sign: 0 nonnegative, 1 negative
 - A two's complement integer represented by a w -digit bit sequence has a range of $-2^{(w-1)}$ [$TMin$] < $B2T(x)$ < $2^{(w-1)} - 1$ [$TMax$]
 - Given bit sequence x in two's complement form: $-x = \sim x + 1$
 - Exception: $x = TMin \rightarrow -x$ evaluates to x [overflow]
 - Sign extension [by k bits, i.e. a w -digit bit pattern $\rightarrow w+k$ digits, preserving value] - copy the most significant bit k times [arithmetic shift]
- Default C integer sizings: **short = 2 bytes, unsigned/signed int = 4 bytes, long = 8 bytes**
 - Integers (ints/constants) considered *signed by default* in C, unless explicitly cast to unsigned (keyword "unsigned") or declared as unsigned (e.g. $x = 5U$;))
 - Comparing unsigned and signed integers: utilizes *unsigned comparison*
 - Also uses unsigned arithmetic over signed arithmetic
 - Can cast unsigned to signed for signed comparison
 - Unsigned comparisons between negatives/positives (< $TMax$) are preserved; otherwise, generally flipped
 - Casting the same bit pattern to unsigned vs signed [two's complement] int in C interprets the number based on the encoding [the cast]
 - Signed vs unsigned take the 1st digit as large negative/positive bias
- Integer addition
 - Problems with integer addition arise due to limited [or constrained] space
 - Exceeding MAX results in overflow; falling below MIN, underflow
 - Unsigned addition to a w -digit bit pattern - $(x+y)$ becomes $(x+y) \bmod 2^w$ (overflows if $x+y > 2^w$)

- Signed addition to a w-digit bit pattern
 - Adding one to TMax evaluates to TMin; subtracting one from TMin evaluates to TMax
- Integer multiplication: multiplying an integer (signed or unsigned) by 2^k equivalent to a leftward shift of k digits
 - Leftmost bits may be discarded
 - Breaking down multiplication factors in terms of powers of 2 then adding & shifting can be faster than true multiplication (i.e. repeated addition)
 - Ex: $14 = 8 + 4 + 2 \rightarrow x * 14 = x * 8 + x * 4 + x * 2 = x \ll 3 + x \ll 2 + x \ll 1$
 - Shifting and adding is faster than multiplying
- Integer division: can be implemented via rightward shifts, similar to reverse multiplication
 - Shifting loses precision – left shifting an unsigned integer k digits gives $\text{floor}(u/2^k)$
 - Adding a bias term (1 less than divisor) changes behavior to always round toward 0 (as opposed to toward -infinity, default behavior of a simple shift)
 - Dividing by y : $(x + y - 1) / y$ [bias for negative division to round toward 0, rather than flooring]
- Memory is byte-addressable: each location stores a byte; later bytes are 4 or 8 bits after
 - Multi-byte quantities: *Big-Endian* vs *Little-Endian* ordering
 - Given a quantity stored in multiple bytes (e.g. addresses $x, x+1, \dots, x+w$) [address $\&x$ given by compiler]:
 - **Big-Endian**: More significant values stored at lower addresses (i.e. most significant value stored at x)
 - **Little-Endian** (x86): More significant values stored at higher addresses (i.e. most significant value stored at $x+w$)
 - Hex quantity 0x123456: more significant (12) -> less significant (34)
 - Big-Endian: 12 -> 34 -> 56
 - Little-Endian: 56 -> 34 -> 12
 - Actual internal contents of bytes unchanged, just outside ordering
 - Orderings within (of bits): most to least significant
- Misc.
 - C: `<limits.h>` declares platform-specific constants, e.g. LONG_MIN/MAX, etc.

x86

Assembly

- A single line [instruction] in Assembly is 8 bytes
- Data types (Assembly):
 - Integer values (1, 2, 4, 8 or bytes)
 - Data values, stored in memory addresses [untyped pointers]
 - Floating point - 4, 8, 10 bytes
 - Code - byte sequences encoding series of instructions
 - Note: no aggregate types (e.g. arrays, structures), just [contiguously allocated] bytes in memory
- Layers of code
 - Machine code – each instruction stored at some address in memory
 - Instructions are variable length: contain a certain number of bits (depending on command) storing needed information (e.g. integer indicating the command, SRC address, DEST address, etc.)
 - Assembly: human-readable version of machine code
- Assembly commands
 - “q” (quad) at the end of a command indicates that it handles 64 bits; also: “l” (long - 32-bit), “w” (word - 16-bit)

Operation	Command	Operands	Operation
Move [copy]	movq	SRC, DEST	Copies value of/at SRC to DEST
Load effective address	leaq	SRC, DST	Copies address at SRC to DST
Add	addq	SRC, DST	Replaces value at DST with SRC + DST
Subtraction	subq		
Multiplication	imulq		Signed
Multiplication	mulq		Unsigned

Left shift	salq/shlq	SHIFTAMT, SRC = DST	Replaces value of SRC with (SRC << 2)
Arithmetic right shift	sarq	SHIFTAMT, SRC = DST	Replaces value of SRC with (SRC >> 2)
Logical right shift	shrq	SHIFTAMT, SRC = DST	Replaces value of SRC with (SRC >> 2)
Exclusive or	xorq		
And	andq		
Or	orq		
Increment	incq	*one operand	
Decrement	decq	*one operand	
Negate	negq	*one operand	
Not	notq	*one operand	
Return	ret	N/A	Terminates function

- **movq** analogous to dereferencing and assigning a value at a pointer's address in C (i.e. `*dest = val -> movq %addr1, %addr2`)
 - If SRC is an immediate, assigns value of that immediate to DEST
 - If SRC is a memory address [i.e. referred to by operator()], assigns value at that memory address to DEST
 - **movzbl** - move from byte (hence the b) to 32-bit (hence the l), filling the remaining bytes with zeros (hence the z)
 - **movslq** - move from long (32-bit) to quad (64-bit), filling remaining bytes by sign-extending (hence the s)
 - When moving 32-bit to 64-bit register, automatically zeroes the extra bits
- **leaq (load effective address):**
 - Is a means of computing addresses without a memory reference/performing pointer arithmetic without actually dereferencing the pointer [i.e. with only a register address] (analogous to `p = &x[i]`)
 - Can use general memory addressing with `D(Rb, Ri, S)` to perform pointer arithmetic (i.e. `SRC = (%rax, %rcx, 2) = %rax + 2 * %rcx`)

- Using the same command with `movq` copies the value at the returned memory address to `DEST`; `leaq` simply copies the returned memory address to `DEST` without dereferencing
- Computing arithmetic expressions $x + k * y$ ($k = 1, 2, 4, \text{ or } 8$)
 - Is an alternative to `addq` that does not overwrite the destination
 - E.g. `leaq(%rax, %rcx, 3), %rdx` places a value of $\%rax + 3 * \%rcx$ in `%rdx` (whether `%rax`, `%rcx` held integers or memory addresses)
- Omitting `SHIFT_AMT` for one of the shift commands will shift by 1

Registers

- Prefix 'r' denotes 64-bit registers; prefix 'e' denotes 32-bit virtual register
 - `%rsp` - reserved for specific purposes (stack pointer), `%rbp` - base pointer
 - `%rbp` indicates 64 bits at some place in the register file; `%ebp` denotes the latter 32 bits of *those* 64 bits in the register
 - `%rax` - 64 bits, `%eax` - 32 bits, `%ax` - 16 bits, `%al` - 8 bits, etc.
 - Assigning to lower-bit portions of a register will zero out upper bits
- Every *register address* (e.g. `%rax`) is a label for an n-bit sequence in register
- X86 contains only 16 distinct integer registers
 - Running out of registers (register coloring (?)) - must then also start to use memory in conjunction with register (register spilling)
 - Note: x86 allows direct access of memory (not all architectures)
 - Only allows 1 access of memory at a time due to physical design restrictions in x86 (e.g. cannot move from memory to another address in memory - must go through registers as an intermediary)
 - Having additional registers prevents spilling, but may result in hardware issues
 - Also requires more bits to specify a specific register in an instruction - increases size of instructions in memory
 - Other architectures may have more or less registers (e.g. ia32 - 8 registers)
- `%rdi`, `%rsi`, `%rdx` used for first three arguments (in that order); `%rax` used for return
 - Registers: `rax`, `rbc-rdx`, `rsi`, `rdi`, `rbp`, `r8-r15` [also `rsp` (reserved)]

Operands

- *Assembly operand types:*
 - **Immediate/literal** - constant integer data
 - Akin to a C constant, but prefixed with \$ (e.g. \$0x400, \$-533)
 - Encoded with 1/2/4 bytes (instruction always allocates 4)
 - Instruction contains an immediate as a constant (i.e. contains the actual value of the immediate, not an address to it)
 - **Register** - [value contained at] one of 16 integer registers (e.g. "%rax")
 - Akin to a variable in C (points at a certain integer register)
 - **Memory** - 8 consecutive bytes of memory at address given by register
 - E.g.: (%rax) refers to the 8 consecutive bytes in memory, at the memory address stored in %rax (%rax contains a memory address - (%rax) follows that memory address and returns the value at that address in memory)
 - Doesn't need to only be referenced as a pointer - can also be treated as a variable [register], a la pointer arithmetic
- *Addressing modes:*
 - Normal ((R), e.g. %rax) returns value at memory address contained in %rax
 - (Rb) = Mem[Reg[Rb]]
 - **General form: $D(Rb, Ri, S) = \text{Mem}[\text{Reg}[Rb] + S * \text{Reg}[Ri] + D]$**
 - D = displacement, Rb = base register, Ri = index register, S = scale (1/2/4/8)
 - Rb automatically added
 - Ri (index register) added, but multiplied by scale
 - Similar to indexing into an array via pointers
 - Scale limited to 1, 2, 4, 8 [bytes] since "multiplication" is just left shift
 - Note: D defaults to 0 (no displ), S to 1 (adds just one of Reg[Ri])
 - Displacement specified by a constant: offset by certain number of bytes
 - Can be used to index into arrays, e.g.
 - Since displacement is a constant, limitations in data type mean displacement can only be a 1/2/4-byte integer (no 8-byte)
 - May or may not address into forbidden/nonexistent memory addresses
- Compiler typically handles allocation of/dealing with registers

Control

- **Condition codes** are special single-bit registers [on the CPU] describing attributes of the most recent arithmetic/logical operation [excluding leaq]
 - Can be used to perform conditional branches
 - Notable codes:
 - CF (Carry flag) - most recent operation carried out of most significant bit
 - Used for detecting unsigned integer overflow
 - ZF (Zero flag) - most recent operation yielded a zero
 - SF (Sign flag) - most recent operation yielded a negative value
 - OF (Overflow flag) - most recent operation resulted in a two's complement overflow (negative or positive)
 - Can also be modified by certain commands [without altering other registers]
 - COMPARE S1, S2 -> S2-S1:
 - cmpb/w/l/q (compare byte/word/double word/quad word)
 - setg [greater] executes if $S2 > S1$ (e.g.)
 - TEST S1, S2 -> S1 & S2: [testb/w/l/q]
- **SET operations** set a single byte (e.g. of a register, such as a single-byte %e* register) to 0 or 1, depending on condition codes
 - Take one parameter (D = destination)
 - **Operations:**

■ sete/setz	D = ZF	[equal]
■ setne/setnz	D = \sim ZF	[not equal]
■ sets	D = SF	[signed negative]
■ setns	D = \sim SF	[signed nonnegative]
■ setg/setnle	D = \sim (SF ^ OF) & \sim ZF	[greater: signed >]
■ setge/setnl	D = \sim (SF ^ OF)	[greater or equal: signed >=]
■ setl/setnge	D = SF ^ OF	[less: signed <]
■ setle/setng	D = (SF ^ OF) ZF	[less or equal: signed <=]
■ seta/setnbe	D = \sim CF & \sim ZF	[above: unsigned >]
■ setae/setnb	D = \sim CF	[above or equal: unsigned >=]
■ setb/setnae	D = ZF	[below: unsigned <]
■ setbe/setna	D = CF ZF	[below or equal: unsigned <=]

- **Jump instructions** cause program execution to “jump” to a specific instruction (changing the program counter/RIP)
 - Break normal sequential execution of instructions
 - An **unconditional jump (jmp)** takes a single address [to be jumped to] as input; taken as either a *label* [directly encoded in the instruction] or **operand* [read from register/memory]
 - Direct jumps are jumps using labels; indirect jumps use **operands*
 - Syntax: `jmp [Label/*Operand]`
 - A label is written as its own line in the program (i.e. the line “.L2:” labels a destination; it can then be jumped to with “`jmp .L2`”)
 - Converted to/replaced by an actual memory address during the linking process
 - **Conditional jumps** jump if and only if a certain condition is fulfilled (e.g. `jge` only jumps if $\sim(SF \wedge OF)$ evaluates as true)
 - Conditional jumps follow notation of SET operations for conditions
 - Can only be direct jumps (i.e. take labels as input)
- *Conditional branching in Assembly:*
 - Conditional jumps can be used to mimic conditional branching (e.g. C if statements)
 - Entail a conditional transfer of *control* (i.e. the program takes a different execution path depending on the evaluation of the condition)
 - Simple, general, but possibly inefficient on modern processors
 - *Pipelining*, process by which modern processors achieve higher performance by “looking ahead” in instructions, may break down for conditional jumps if the processor cannot predict jump/predicts incorrectly
 - “Falling through” (i.e. not following `condjump`) is typically faster than following the conditional jump for optimization purposes
 - **Conditional moves** can be used to mimic conditional assignment (e.g. C ternary conditional operator)
 - Conditional moves also follow SET operation condition syntax (e.g. `cmovge` = move if greater/equal)
 - Entail a conditional transfer of *data* (i.e. the execution path of the program is static, but the data itself might change based on the condition)
 - More restrictive than conditional jumps, but also more efficient

- Both sides of the ternary are always computed when using a conditional move, no matter the value of the condition
 - May cause problems, e.g. if the two expressions are expensive to compute, would cause errors [are risky], or could cause issues/side effects (e.g. if both modify an external variable)
 - Ex: “ptr ? *ptr : 0;” could attempt to dereference a null pointer, even if “ptr” evaluates to false
- Looping in Assembly:
 - C-style loops can be mimicked/implemented in Assembly using a combination of conditional tests and jumps
 - C do-while(condition): *body statements [loop body]* -> *conditional jump to top [loop condition]*
 - C while has two main implementations in GCC:
 - *Jump-to-middle*: *unconditional jump to bottom* -> *body statements [loop body]* -> *conditional jump to body statements [loop condition]*
 - Less optimized (-Og [no optimizations]), due to extra jumping compared to guarded-do
 - *Guarded-do*: *conditional jump skipping loop [loop condition, initial check]* -> *body statements [loop body]* -> *conditional jump to body statements [loop condition]*
 - Effectively transforms while loop into a do-while loop with an extra conditional jump before the loop itself
- C switch statements can be implemented using either a straightforward if-else conditional branching approach, or using a special data structure called a *jump table*
 - A **jump table** is an array where each entry *i* contains the address of the instruction to be jumped to if the switch index == *i*
 - Allow for constant-time switch indexing via referencing
 - Is more efficient than traditional if-else chains in situations with a significant amount of cases (e.g. >4) that only span a small range of values (such that the array does not take up too much space)

- Composed of multiple quads in sequence (i.e. `.align 8` (indicating each value is sized 8 bytes) \n `.myLabel: quad .LabelForCase1` \n `quad .LabelForCase2` \n ...)
- `Jmp *.L4, *index as register value*, 8)`
 - Performs an indirect jump, to a memory address relative to `.L4, + 8 * index`
- Does offset the switch cases (e.g. 5, 6, 7 -> 0, 1, 2)
 - Performing unsigned comparisons `ja` [jump above] filters out negatives - notably unsigned "`x > 6`" returns true for all positive `> 6`, but also all negative `> 6` [since interpreting a negative two's complement as unsigned = large [positive] integer]
- Using conditional jumps converts the switch to an if-else chain
 - Notably, instructions for each case are likely stored sequentially and on top of each other; as such, if a case does not explicitly jump to the done state upon concluding, the code will otherwise simply "fall through" to the next case (similar to forgetting `break`; in a C switch)
- Can also be implemented as a form of tree

Procedures

- A **procedure** is a named, independent section of code, callable by a larger body of code, that takes a designated set of arguments and performs a specific task
 - Are analogous to *functions* in C/C++
 - Similar to C/C++ functions, a procedure may or may not return a value
 - Can be referenced/called by other bits of code as a form of abstraction
 - Calling a procedure in Assembly: *call *label** [*callq *label**]
 - Are called by the memory address of the procedure [the first instruction of the procedure]
- Mechanisms for transferring control between procedures (via machine instructions):
 - *Passing control* - moving the program counter from one procedure to another
 - *Passing data* - passing values between procedures (i.e. as either input to the subprocedure, or output from the subprocedure)
 - *Memory allocation* - the subprocedure will need to allocate/deallocate memory to handle its own local variables
- *Picture of memory*:
 - **Stack** - at the top of memory (highest addresses), **grows downward** (i.e. toward lower memory addresses)
 - Towards the bottom of memory: text - contains instructions, e.g. (pointed to by program counter), data (global variables), heap (malloc'd/dynamically allocated memory - grows upward)
- The **x86-64 stack** is a stack data structure used for memory management and allocation/deallocation between procedures
 - Motivation: The most recent procedure called will always be the only procedure allocating memory, and all of *its* memory will be deallocated when it exits [before the memory of earlier procedures is touched]. As such, a stack is a good way to represent this pattern of allocation/deallocation
 - Is dissimilar from a stack in the sense that any address can be accessed
 - Is generally used by x86-64 when more space is needed than can be accommodate by registers; is also referred to as the *stack frame*
 - Registers are generally preferred for space and time efficiency
 - Terminology: the stack top is the active end, where insertion/deletion occurs

- Notes on the x86-64 stack:
 - The stack always grows towards lower memory addresses
 - The `%rsp` register points toward the top of the stack
 - Can allocate/deallocate space on the stack by decrementing/incrementing `%rsp`, respectively
 - ***pushq*** SRC writes SRC to `%rsp`, decrements `%rsp` by 8 [bytes] (allocates space)
 - ***popq*** DEST writes value at `%rsp` to DEST, increments `%rsp` by 8 (deallocates)
 - DEST must be a full 64-bit register
- Mechanisms for transferring control between procedures:
 - *Passing control* - moving the program counter from one procedure to another
 - Whenever a procedure is called, a return address is always added to the stack, indicating the instruction to resume at once the procedure exits
 - Return address is first item added to the stack upon a procedure call, even before the jump to the procedure is executed [decrement `rsp`; add return address; jump]
 - Assembly command `ret` pops the return address from stack, then jumps to it (resuming program)
 - To reach the return address - compiler determines how much space is allocated in a certain stack frame; at the end of procedure, simply moves stack pointer back that much space, which will be back at return address
 - Can decrease overhead by inlining functions
 - *Passing data* - passing values between procedures (i.e. as either input to the subprocedure, or output from the subprocedure)
 - First six arguments for procedure calls are held by registers `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`; return value is held by `%rax`
 - Stack space for additional arguments is only allocated when needed (i.e. when `num_args > 6`)
 - *Memory allocation* - the subprocedure will need to allocate/deallocate memory to handle its own local variables
 - A programming language can support recursion only if its code is reentrant (allows multiple simultaneous instantiation of a single procedure)

- Needs some place to store the state of each instantiation (e.g. local variables, arguments, return pointer, etc.)
- Stack allocated in **frames** - memory regions storing the data of a single procedure call/instantiation
 - Is typically allocated on function call (push by “call”/callq instruction), deallocated on return (“ret” instruction)
 - Contains return information, local storage, and any temporary storage (as needed)
 - Allows for handling of recursion without any special considerations
 - *Contents of the frame (in order):*
 - Caller frame: ends with arguments of the call to new procedure (if num_args > 6), return address
 - Pointer to old %rbp (optional)
 - Procedure frame [callee]:
 - Saved registers (to be restored on procedure exit)
 - Local variables [if registers are insufficient]
 - Argument build [any arguments for a subsequent function call]
 - %rsp [stack pointer] points to top
- Using registers for temporary storage
 - A procedure calling another procedure may cause issues relating to memory if both are modifying/accessing the same registers for temporary storage
 - Conventions:
 - *Caller saved*: caller saves any temporary values it needs (e.g. in registers that may be overwritten) in its own stack frame before procedure calls
 - Assumes registers will be overwritten
 - Registers: %rax, argument registers (%rdi, ..., %r9), %r10, %r11
 - *Callee saved*: callee saves temporary values of caller (e.g. register values) in its own frame, restores them before exiting
 - Registers may still be changed in the procedure, but will be restored before returning
 - Registers: %rbx, %r12-%r14, %rbp, %rsp
 - Stack overflow - writing past the bounds of allocation on the stack
 - E.g. allocating a buffer, and then writing past the the end of it

Data

- **Arrays** are implemented as single contiguous regions of memory, holding variables of a certain type in sequence
 - An array of length L containing variables of type T ($T\ A[L]$) will take a contiguously allocated region of $L * \text{sizeof}(T)$ bytes in memory
 - An array variable can thus be interpreted as a pointer to the corresponding region in memory
 - Can be indexed into via memory addressing: $(\text{arr}, \text{index}, \text{sizeof}(\text{var}))$
 - A **multidimensional array** can simply be implemented as an array of arrays
 - Ex: A 2D array with R rows and C columns, holding variables of type T ($T\ A[R][C]$) will take a region of $R * C * \text{sizeof}(T)$ bytes in memory
 - Individual subarrays can be accessed via memory addressing
 - $\&A[i][j] = \&A[0][0] + i * C * \text{sizeof}(T) + j * \text{sizeof}(T)$
 - Are ordered row-major: structured as a vector of rows
 - Implementations:
 - Simple array of array objects (*static array*)
 - Array of pointers to arrays
 - Requires one additional memory address dereference, but frees subarrays from needing to be contiguous in memory
 - NxN matrix handling in C:
 - *Fixed dimensions, known at compile time*: handled as a traditional array
 - *Variable dimensions, explicit indexing*: handled as a pointer, then offset
 - Traditional method for implementing dynamic arrays
 - *Variable dimensions, implicit indexing*: indexing into arrays (e.g. $a[i][j]$, for array $a[n][n]$) more recently supported by gcc
- **Structures** (e.g. classes) are represented as singular blocks of memory, containing all of the structure's fields (i.e. member variables)
 - Overall size + positions of fields determined by compiler at compile time
 - Machine code does not understand the structures in the source code
 - C: fields ordered by declaration (explicitly not reordered for efficiency)
 - Strategies for saving space: putting large data types first
 - Ex: array fields have the requisite memory allocated at compile time

- **Alignment/Aligned data:** If a primitive [integral type] requires ***K bytes*** of memory to store, it must be stored at a memory address that is ***a multiple of K***
 - Ex: char (1 byte), short (2 bytes), int (4 bytes), long (8 bytes)
 - Is required by some OSes; recommended for x86-64
 - Some OSes will have an explicitly-defined K (block size for memory/cache transfer) [e.g. 8 bytes on some systems]
 - If an OS has a fixed 8-byte block size, it will also require input addresses be multiples of 8 [due to the mechanism of dividing cache blocks/lines]
 - Makes accessing memory + loading/storing values more efficient, by minimizing the amount of blocks/pages needed to transfer values
 - Ensures a single primitive is only on a single block/page
 - Compiler will insert gaps in memory as needed to ensure alignment
 - *Unaligned data* has no such requirement
- **Conditions for alignment:**
 - **Within structs:** each element must satisfy its own alignment requirement
 - **Overall placement:** each structure has an alignment requirement equal to that of the largest alignment requirement of its elements
 - Initial address + structure size must be multiples of K
 - Arrays of structures must satisfy alignment requirements for all elements
 - Padding may be added between structures
 - Other: alignment requirement for an array is the alignment requirement for the elements of the array

x86 Memory

- X86-64 memory layout:
 - *Dynamic memory regions:*
 - **Runtime stack** (local variables) begins at the top, grows downward toward lower addresses [8 MB limit]
 - **Heap** (dynamically allocated variables) begins near the bottom, grows upward toward higher addresses [allocated by malloc(), calloc(), new()]
 - *Static memory regions:*
 - Statically allocated data (global vars, static vars, string constants) stored under the heap
 - Text/shared libraries (machine instructions) stored under the data
 - Begins at hex address 0x400000000000
 - Below text - reserve data (e.g. memory map registers)
- **Buffer overflow** - attempting to access objects past the memory size allocated for an array
 - e.g. attempting to access index 5 of a 4-element array
 - Results in possible security vulnerabilities (namely code injection)
 - Possible causes:
 - Unchecked lengths on string inputs
 - Bounded character arrays on the stack [stack smashing]
 - Unix string functions (e.g. gets [read from stdin into C string]) do not provide a means of specifying read limit
 - Other functions: strcpy, strcat, scanf/fscanf/sscanf
- **Code injection** - inputting a string containing executable code and overwriting the return address of a function to point to said executable code, such that it is run when the function returns
 - Allows for running arbitrary code from a remote machine
 - Location of ret address needs to be known (i.e. attacker has to have run program and found ret address, and ret address must be the same across calls)
- *Avoiding buffer overflow*
 - **Avoid overflow vulnerabilities:**
 - Use library string functions that allow for specifying read limit lengths
 - **System-level protections:**

- **Random stack offsets** allocate a random amount of space on the stack whenever a program is run, shifting addresses for the entire program
 - Makes prediction of exact memory address difficult
 - E.g. giant block of padding before main frame
 - **Non-executable code segments:** x86 has three types of permissions: read (always true), write (opt-in), and execute (opt-in) permissions
 - Translation look-aside buffer in MMU translates virtual addresses to physical addresses (allows for marking memory non-executable)
 - Can mark stack as non-executable, since stack is generally supposed to contain only data [not instructions]
- **Stack canaries** can be placed at the end of a stack beyond a buffer, check for corruption before exiting function (GCC: `-fstack-protector`)
 - Any buffer overflow injections will then modify the canary as well - incorrect canary -> corruption
 - %fs - one of set of system registers describing memory (can be the canary)
- **Return-oriented attacks:**
 - String together fragments from existing executable code (e.g. stdlib library code)
 - Will be executable and thus runnable
 - Make program from *gadgets*: any sequence of instructions that ends in ret (0xc3)
 - Code positions fixed from run to run, always executable
 - Uses tail ends of existing functions to string together a program
 - Overwrite return address to point to gadget
 - Can index into an instruction or even specific bytes in an instruction
 - Each gadget ends in a return; can layer gadgets consecutively on the stack to call gadgets in sequence
- **Union** - a data structure where all fields are stored in the exact same region of memory
 - Storage is allocated according to largest element
 - Can only use one field at a time
 - Can be used to handle bit patterns
 - Ex: declaring a union with an unsigned int and signed int will allocated space for a single int; referencing the unsigned int will return the bit pattern in that space interpreted as a uint, vice versa for signed int

Floating Point

- **Fractional binary:** Bits represent powers of 2, similar to integers; bits to the left of a binary point represent powers ≥ 0 , bits to the right represent powers < 0 (fractional)
 - Limitations: can only approximate numbers not expressible in terms of powers of 2, only have one binary point (limiting the possible range of values)
- **Floating-point (FP) numbers** represented as specially-interpreted bit patterns
 - Created to replace fractional binary; provide larger possible range of values
- **IEEE Standard 754 (1985)** - uniform standard for floating-point arithmetic
 - Driven by numerical concerns, making standards for rounding, overflow, underflow
 - Not necessarily hardware-efficient
 - Numerical form - sign bit as the MSB [similar to ints], exponent E (exp), significand/mantissa M (frac)
 - Significand normally a fractional value in the range $[1.0, 2.0)$
 - Value: $float = (-1)^s * M * 2^E$
 - **Encodings:**
 - **Single-precision [32 bits]:** sign bit, 8 exp bits, 23 frac bits
 - **Double-precision [64 bits]:** sign bit, 11 exp bits, 52 frac bits
 - **Extended-precision (Intel only):** 1 sign bit, 15 exp bits, 63/64 frac bits
- Normalized [normal] vs denormalized [subnormal]] values
 - **Normalized values** take the form $(-1)^s * 1.[frac_2] * 2^E$
 - **Frac field** contains an implied leading 1 (saves one bit of space)
 - Significand may be padded with zeros to fit space
 - **Exponent** will not be all 1s, all 0s [indicates normalized value]
 - E takes the value of exp [exponent bit field] - bias
 - exp interpreted as unsigned int
 - Makes sorting floating-point numbers easier
 - **Bias** = $2^{k-1} - 1$, where k is number of exponent bits
 - Fixed by type size: single-precision: 127, double: 1023
 - **Denormalized values** take the form $(-1)^s * 0.[frac_2] * 2^E$
 - Significand contains an implied leading 0
 - **Exponent** will always be all 0s; $E = 1 - \text{bias}$ always
 - E is fixed; -126 for floats

- In conjunction with leading 0, means denormalized values effectively have exponent of $[\text{min_normalizedE} - 1]$
 - Used when normalized exponent exceeds values
- **Exceptional cases:**
 - Exp field = all 1s, frac field = all 0s indicates **positive/negative infinity**
 - No wrap-around behavior as an integer overflow
 - Exp field = all 1s, frac field not all 0s indicates **not-a-number/NaN**
 - 0 - all zeros
- Denormalized used for values closer to 0; normalized for values farther from 0
- Floats can utilize unsigned integer comparison [once the sign bit is compared]
 - Infinity vs normalized vs denormalized comparisons work, with the exception of NaNs [may be evaluated as larger than infinity/smaller than negative infinity]

Floating-Point Arithmetic

- Involves first computing an exact value, then fitting into a desired precision
 - Value may be *truncated* to fit into frac, or *overflow* if the exponent is too large
- Rounding modes: towards zero, towards +infinity, towards -infinity, round-to-even
 - *Round-to-even* - default rounding mode in most computers
 - Rounds up or down to nearest whole value if not halfway between whole values; rounds to nearest even value if halfway
 - Other rounding modes arithmetically biased in one direction (will add up bias over time); round-to-even is more roughly random in direction of rounding ("even" value: least significant frac bit = 0)
 - Floating-point values:
 - Even when MSB is 0; "halfway" occurs when the digits to the right of the rounding position are 1000....000 [1 followed by all 0s]
- *Float multiplication:*
 - Sign: Exclusive or'd; significands multiplied directly; exponents added
 - Other operations: shifting if new significand ≥ 2 , overflowing to infinity if E out of range [float saturation], rounding M to fit precision
- *Float addition:*
 - Signed align & add sign bit, significand

- May result in difficulties when signed align + add results in a number with more digits than the frac portion can accommodate
 - Will result in truncating the frac portion when rounding
 - **Consequence: Floating point addition is not associative**
 - Exponent of 1st taken
 - Fixing potential errors: shift [left or right] significand as needed, overflows to infinity, rounding M to fit frac precision
- C provides for *float* (single-precision - 4 bytes), *double* (double-precision - 8 bytes)
 - Int vs float: float has a larger dynamic range than int, but ints have more granularity than floats (32 vs 23 numerical bits)
 - Int/float/double conversions change bit representations
 - double/float to int truncates fractional portion (rounds toward zero)
 - Not defined when out of range/NaN; generally sets to TMin
 - Int to double is an exact conversion; int to float may need to round
- **Floating-point (FP) numbers** are stored in special *XMM registers*
 - 16 XMM registers - each XMM register is 16 bytes
 - An XMM register can hold:
 - 4 32-bit/8 16-bit/16 8-bit integers, 1 or 4 single-precision floats (32 bits each), 1 or 2 double-precision floats (64 bits each)
 - Have many special operations related to dealing with FP numbers
 - Require special operations for transferring to/from memory (*vmov*), converting to/from integers
 - Any FP operations referencing memory are scalar operations (operate on individual, not packed, values)
 - SIMD operations operate on packed values
 - Converting FP values to integers performs truncation, rounding values toward zero
 - XMM register conventions:
 - Arguments passed in `%xmm0`, `%xmm1`, etc.
 - Result stored in `%xmm0`
 - All XMM registers are caller-saved

Optimization

- Compiler has two functions: parsing the language
 - Compilers may try to parse languages into an intermediate level, optimize, and then finally generate language
 - Intermediate level aimed to be consistent across different language + language parser combos
- Optimized compilers provide efficient program-machine instruction mappings, reducing the constant factors of programs
 - In terms of register allocation, code selection/ordering [scheduling], dead code elimination, removal of minor inefficiencies
 - Compiler is designed to be *conservative*; limitations:
 - Cannot alter program behavior, even if only to safeguard against errors
 - The program itself may limit/hide opportunities for optimization
 - Most optimize only within individual procedures, based on static info
 - Does not see runtime inputs, e.g.
 - Have difficulty with potential optimization blockers: memory aliasing, procedural side-effects
- General optimizations (programmer or compiler)
 - **Code motion**: reduce instances of redundant/repeated calculations of one value
 - Can share common subexpressions
 - Ex: split $\{5 * i + 1, 5 * i, 5 * i - 1\} \rightarrow x = 5 * i; \{x + 1, x, x - 1\}$
 - **Reduction in strength**: replace costly operations with cheaper ones
 - Ex: replace multiplications with shifts
 - Dead code elimination, code hoisting
- Compiler optimization blockers:
 - *Procedure calls*: compiler treats procedure calls as black boxes, and generally avoids optimizing around them
 - Procedures may have side effects, alter global variables, etc.; cannot be freely moved around the code
 - *Inlining* - replacing function calls with simply splicing in the function body can allow the compiler to make optimizations to/around it
 - Removes the benefits of using a function

- **Interposition** - functions imported dynamically (e.g. from the OS, e.g. stdlib) may not be imported until linkage time
 - Removes need to recompile [becomes modular], but means compiler cannot optimize around it
- Branching
- **Memory aliasing** (disambiguation): a single memory location may be referred to by multiple different memory references; compilers generally hesitant to optimize around memory references as a result
 - May occur in the case of memory arithmetic, esp. with variables
 - Using local variables avoids this, so long as the compiler can know no pointers to the variables will ever be generated
- Arrays & loops with arrays may be difficult for a compiler to optimize around, if the length is not known at compile time
- **Loop unrolling** - trying to reduce loop iterations, increase work per iteration
 - Techniques to avoid **dependency chains**: Reassociation (reordering operations), separating accumulators
 - Can use local variables instead of pointer references (i.e. array stores) to eliminate store/load dependencies
 - Loops in general are difficult to optimize around - a computer may not know what to set instruction counter to, if the instruction that computes said value is not yet known
- **Parallelism**: modern processors can execute multiple instructions in parallel; can be exploited to boost performance on an instruction level
 - **Instruction-level parallelism (ILP)** - finding independent instructions that do not overlap in terms of the data accessed, such that they can be executed in parallel
 - Alt: thread-level parallelism (TLP) - used by GPUs, e.g.
 - Still limited by data dependencies, + lack of associativity/distributivity in floating-point arithmetic
 - Compilers generally do not perform such optimizations
 - **Out-of-order execution (OoOE)** - hardware-level optimization, “finds” opportunities for parallelism by freeing program to perform operations out-of-order
 - Involves performing operations out-of-order, but delaying the write-back to mimic sequential execution

- *Performance metrics:*
 - **Latency** – the time to execute a single instruction
 - Latency bound - the minimum time it takes for an operation to complete
 - **Throughput** – the number instructions executed per cycle (analogous to capacity)
 - **Cycles per element (CPE)** - notation for expressing performance of programs dealing with vectors and lists
 - Expressed in terms of the length of the vector/list (n)
- *Superscalar processor* - processor capable of issuing and executing multiple instructions in a single cycle (most modern CPUs are superscalar)
 - Are typically retrieved from sequential instruction stream, scheduled dynamically
 - Can be used to take advantage of ILP without extra programming effort
 - Instructions: fetch instruction, decode instruction, perform operation, write back
 - Registers are actually just logical registers, mapped to physical registers (uses register stations)
- Modern CPUs composed of two halves - instruction control and execution
 - Instruction control contains instruction cache + decoder
 - Fetch control used in the case of branching, to determine which instructions to fetch
 - Retirement unit contains register file; used to store results of operations before writing to registers as part of retirement (finishing an instruction)
 - Modern CPUs divide execution components into distinct **functional units**, handling different operations (e.g. load, store, arithmetic, branch, etc.)
 - May have more than one functional unit for a single task (e.g. arithmetic)
- *Pipelined* functional units divide computations into stages, pass partial computations from stage to stage
 - If a computation must pass through 3 stages M1, M2, M3: once it completes M1 and is in M2, M1 is now free to start another computation before the first computation has “finished”, e.g.
 - Latches/blocks (?): registers holding intermediate results of computations
 - Can be used to begin new computations before the original finishes, decreasing total number of cycles required (increases throughput, but not latency)
 - Haswell CPUs contain 8 functional units
- Branching:

- Challenge: Instruction control unit must work ahead of execution unit to generate enough operations for execution unit to stay busy, but cannot easily determine where to fetch when a conditional branch is hit
 - Cannot resolve which branch to take until branch/integer unit determined
- Branch prediction: guessing the branch that will be taken, and begin executing at predicted position (but without modifying registers, memory)
 - Forces reloading of pipeline if misprediction
- Performance optimization: general tips
 - Good compiler, compiler flags
 - Write good code
 - Watch out for hidden algorithmic inefficiencies, especially inside loops
 - Make code compiler-friendly
 - Reduce optimization blockers: procedure calls, memory aliases
 - Tune code for machine
 - Take advantage of instruction-level parallelism
 - Avoid unpredictable branches
 - Make code cache-friendly
- Computer architectures:
 - **Single-instruction, single-data (SISD)** - each instruction operates on only a single stream of data
 - **Single instruction, multiple data (SIMD)** - applying a single instruction simultaneously to multiple streams of data (e.g. through parallelism/pipelining)
 - GPU divergence - code may act differently on different threads
 - Lacks flexibility, but reduces complexity of processor
 - Implemented with *YMM registers* - registers capable of holding multiple values simultaneously (e.g. in vector format)
 - 16 YMM registers, 32 bytes each
 - Can be used with vector operations (AVX) - special instructions acting across the values in a YMM register
 - Requires functional units capable of accommodating this
 - Multiple instructions, multiple data (MIMD)

Memory

Memory in Computing

- *CPU-memory gap*: the gap between CPU cycle times [actual & effective cycle times] and memory seek/access times has been widening over time
 - Applies to all forms of memory (disk drives, SSDs, DRAM/SRAM)
- **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 more likely to be referenced again in the near future
 - Ex: referencing the same variables repeatedly, cycling through the same instructions in a loop
 - **Spatial locality** - items with addresses near each other tend to be referenced close together in time
 - Ex: adjacent items in an error, reading of instructions in sequence
 - Well-written programs tend to exhibit good locality
- **Memory hierarchy** - an approach for organization of memory and storage systems, keeping in mind the benefits/drawbacks of various memory types + program properties
 - Ex: a hierarchy might have registers at the top, 3 levels/lines of SRAM cache below, main memory (DRAM), and finally secondary storage (local disks, web servers)
 - Higher-up memory types use storage formats with less capacity, but which are faster in terms of accessing, reading/writing
 - Each storage device in the hierarchy serves as a cache (of sorts) for the device below it

Caches

- **Cache** - a smaller, faster storage device used as a staging area for a subset of the data in a larger, slower storage device
 - Due to locality, computers can move recently-referenced data from memory to cache as a means of increasing read/write speed
 - **Cache memories** - small, fast SRAM-based memories on the CPU, managed automatically in hardware

- Hold frequently-accessed blocks of memory, and are generally the first location searched by the CPU
 - Intel Core i7 has three levels of caches: the first two are divided between cores, and the third level is a unified cache for all cores
- *Cache terminology:*
 - A larger memory device is usually referred to as being partitioned into **blocks**; a cache holds copies of a subset of these blocks
 - **Blocks** - information unit for transfer between cache, memory
 - Holds data bytes + metadata: valid bit (indicating if data is valid cache data), tag (indicating source location in DRAM)
 - Caches divided into **sets**, divided into **lines/blocks**
 - Cache size: $C = S (\# \text{ sets}) * E (\# \text{ lines}) * B (\text{block offset/size})$
 - Number of physical address bits: $m = t + s + b$ ($t = \# \text{ tag bits}$; $s = \# \text{ set index bits} = \log_2(S)$; $b = \# \text{ block offset bits} = \log_2(B)$)
 - Cache association:
 - **Direct-mapped**: exactly one cache line per set
 - A single given memory address only has one possible line
 - Fast (no need to search across lines), but increases miss rate: references to any addresses on same line result in a miss
 - **Fully associative**: one set containing all cache lines
 - A single given memory address can occupy any line
 - Most complex: decreases miss rate, since all blocks are contained in one set, but requires searching entire set
 - **Set associative**: anything in between direct, full
 - A program requesting memory from a block that has been copied to the cache can draw directly from the cache (a **hit**)
 - **Hit time** - time needed to deliver a cache line to the processor (~4 clock cycles for L1, 10 for L2)
 - A program requesting memory from a block not in the cache must first copy the block from memory to cache, then draw from cache (**miss**)
 - **Placement policies** determine where the new block is placed in the cache; **replacement policies** determine which block is replaced

- **Miss rate** - fraction of memory references that are misses (3-10% for L1, possibly <1% for L2)
 - **Miss penalty** - additional time required when a miss occurs (50-200 cycles for main memory; has been increasing)
- Writing cache-friendly code
 - Focus on the locations where the most computations + memory accesses occur, e.g. in the inner loops of core functions
 - Can utilize locality to minimize misses in inner loops
 - Using repeated references to variables boosts temporal locality
 - Stride-1 reference patterns boost spatial locality
 - Note: spatial locality more important for loads than for stores
- *Memory throughput* (read bandwidth) - number of bytes read from memory/second (MB/s)
 - *Memory mountain* - a measure of memory throughput as a function of spatial, temporal locality (i.e. as a 3D surface)
 - Throughput generally increases with smaller strides, cache sizes
 - Can be used to characterize memory system performance
- **Tiling** - when performing computations involving matrices/matrix arithmetic, can perform operations on individual block matrices instead to improve performance

Parallelism

- Moore's law - semiconductor density doubles every 18 months
- Single-core hardware performance hits the power wall - power consumption increases exponentially relative to scalar performance [thermal throttling]
 - Mobile CPUs with shallow pipelines use less power
- Multi-core processors avoid increased power consumption of single-core
 - May share caches for communication
 - Require applications (programmers) to split across cores
 - Different cores may be specialized for different tasks
- Definitions:
 - **Concurrency** - a system state where multiple tasks are *logically* active at a time
 - Tasks logically occurring at once are not necessarily running simultaneously in real-time (e.g. computer might be switching control)
 - **Parallelism** - a system state in which multiple tasks are *actually* active at a time
 - Parallelism implies concurrency; vice versa is not necessarily true

OpenMP

- OpenMP - set of compiler directives + libraries (API) for writing multithreaded (parallel) applications for Fortran, C, C++ (#include <omp.h>)
 - Runs at program layer (like compiler, env variables), system layer (runtime library)
 - Constructs are mostly compiler directives (included using pragma statements; imported during compilation)
 - Apply to a structured block - block of one or more statements with point of entry at top, point of exit at bottom
 - Ex: `#pragma omp parallel num_threads` (creates multiple workers)
 - Runs a given structured block once for each thread
- Shared memory programming
 - **Process** - a single instance of a program execution
 - Contains execution context - resources associated with program execution
 - May use specialized cores depending on the task/program
 - Simultaneous multithreading (hyperthreading) - running multiple processes simultaneously on a single core

- Can be used in the case that each individual process has lots of downtime that would waste processor time, e.g.
 - **Threads** - “lightweight processes”
 - Share process state among multiple threads - reduces cost of switching
 - Operate on an MIMD/SPMD (single-program, multiple-data) model
- OpenMP: a single application (**process**) may have multiple **threads** running
 - Each thread has their own private memory; interact with other threads through reads/writes to **shared address space**
 - Synchronization used to ensure correct results
 - Threads may run in an interleaved fashion (as determined by OS scheduler)
 - Result in no guarantees in terms of program ordering
 - Uses a **fork-join parallelism model** - a master thread spawns a team of worker threads over the course of execution [fork], synchronizing intermittently [join]
 - Parallelism added/removed incrementally, as needed, to hit performance goals [sequential program becomes parallel]
 - Worker threads may make their own sub-threads (nested parallel regions)
 - `#pragma omp master` - only master thread executes block
- OpenMP - multithreading, shared address model
 - Different threads communicate by sharing variables
 - Unintended sharing causes **race conditions**: when program’s outcome changes depending on thread scheduling (prevented via synchronization)
 - Can change manner of data access to prevent expensive synchronization
- OpenMP programming
 - `omp_set_num_threads` requests certain number of threads; `omp_get_thread_num()` returns thread ID (can only be run outside of/before parallel sections)
- **Synchronization** - bringing one or more threads to well-defined, known points of execution
 - Synchronization **barriers** may prevent a program [main thread] from continuing until all threads have hit a certain point [the barrier]
 - `#pragma omp barrier` - creates barrier
 - Implied barriers at end of worksharing/parallel constructs; can be removed with `nowait` clause
 - **Mutual exclusion** - defined blocks/portions of code [**critical regions**] that only one thread can execute

- Upon hitting a critical region, only one thread can perform the read/write at a time (temporarily stops parallelism)
 - `pragma omp critical` declares one-statement critical region
- `pragma omp atomic` is much lower overhead than `omp critical`
 - Requires subsequent statement to be one of the following forms: `x binop = expr`, `x++/++x`, `x--/--x`
 - Requires clause specifying operation type:
 - `update` [default] – protects an update of value
 - `capture` – protects an update and assignment
 - `read` – protects a load; `write` – protects a store
- Parallelism - scaling issues
 - **False sharing** - accesses of multiple independent data elements sitting on the same cache line by different threads may force the cache to continually cycle between different points in the cache
 - Solution: pad arrays so elements are on distinct cache lines
 - **Cache coherence** – if multiple threads have cached the same memory address, one thread writing to that address will invalidate all said other caches
 - Snooping - a cache listens to bus transactions
 - Does not scale well
 - Directory - a directory in cache contains who (which thread) has what block, and in what state
 - L3/L2, typically
 - MOESI [modified owned exclusive shared invalid]

Worksharing

- **Loop worksharing** - splitting up loop iterations among threads in a team
 - Used for loops of unknown/dynamic runtime, e.g.
- **`pragma omp for`** [omp do in Fortran] splits up execution of loop iterations
 - Can be combined with parallelism construct: **`pragma omp parallel for`** for parallelized worksharing (splitting up iterations between threads)
 - Equivalent to `pragma omp parallel`; `pragma omp for`
 - Loop variable implicitly made private to each thread

- Only applies to outermost loop in a nested for loop; can be combined with `collapse(depth)` clause in the case of perfectly nested inner loops
- **Loop-carrying dependencies** - cases where each loop iteration depends on the results of previous iterations
 - May increase efficiency, but prevent out-of-order execution
 - Can be removed to take advantage of out-of-order execution
- **Schedule** clause - affect mapping of loop iterations onto threads
 - `pragma omp for schedule(dynamic)`, e.g.
 - Types:
 - Static - handing out blocks of iterations
 - Inefficient in the case that one thread takes longer than the others, e.g., but does not incur much overhead
 - Dynamic - each thread grabs a certain number of iterations off a queue, until all iterations have been handled
 - Guided - threads dynamically grab blocks of iterations
 - Blocks initially large; shrink as calculation proceeds
 - Runtime - Schedule, chunk size taken from `OMP_SCHEDULE` environment variable (or runtime library)
 - Auto - schedule left up to runtime choice
 - May not choose the other predefined types
- OpenMP reduction: `pragma omp *statements* reduction (op : list)`
 - Parallelizes a loop: a “global variable” is separated into different local variables [one per iteration], then combined at the end (more scalable than critical)
 - Operators: +, *, -, min, max, &, |, ^, &&, ||
- OpenMP sections:
 - Defines task-level parallelism - gives different structured block to each thread
 - Max number - number of active threads
 - Syntax: `#pragma omp sections -> #pragma omp section`
- OpenMP lock routines
 - Lock a single piece of data to only allow writing by a single thread
 - May lock a single element in an array, allowing for access by other threads to all other elements

- Is an alternative to critical sections - allows for parallelism to be used without having errors, in the case that threads may be modifying the same data but are not dependent on each other
 - Deadlock - locks may be placed in such a way that no thread can act (threads may have locked each other's data, e.g.)
 - Syntax [within a `#pragma omp parallel for`]:
 - `omp_init_lock(memory_addr)` allows for creating a lock a memory address
 - Repeated for each element in an array, e.g.
 - `omp_set_lock(memory_addr); omp_unset_lock(memory_addr)`
 - Operates by invoking a system call (similar to atomic)
 - `omp_destroy_lock(memory_addr)`
 - Nested lock - can be accessed if unlocked, or by locking thread
 - Must be unset as many times as was set to unlock
- Data:
 - *Shared memory programming model*: most global/externally-allocated variables are shared, local [thread-specific] variables are private
 - Can attach clauses to change storage attributes for constructs: SHARED, PRIVATE
 - `FIRSTPRIVATE(varname)` gives each thread a private variable (with name `varname`), with initial value the value of the variable (with name `varname`) in shared memory [copy-constructed]
 - Private variable is not initialized otherwise
 - `LASTPRIVATE(variable)` - private variable updates shared variable with value from last sequential iteration [functionally last]
 - Set default permissions: `default(private|shared|none)`

Tasks

- Non-deterministic work (i.e. exact number of steps not known) difficult for worksharing
 - Recursion (e.g. pointer chasing)
- **Tasks** (OpenMP) - independent work units, containing: code to execute, data environment, internal [control] variables (ICV)
 - Tasks are added to a queue [buffer]; threads pull tasks from the queue and perform work dynamically

- May also be deferred, or executed immediately (runtime system decides)
- Syntax: `#pragma omp task` will add the following structured block to the task queue
 - Tasks are automatically handled by other threads, if inside omp parallel
 - Structured block: default next line [e.g. function call]/curly brace contents
 - Task barrier: wait until all tasks in buffer are completed, before continuing
 - `#pragma omp taskwait` [omp barrier also does the same]
 - `#pragma omp task` within `#pragma omp parallel` will create one of that task for each thread
 - `#pragma omp single { *code* }` [inside an omp parallel] - only one thread executes the contained code
 - Has an implicit barrier at the end [nowait clause -> no barrier]
- `#pragma omp task`
- Task construct - explicit tasks
 - Create team of threads [pragma omp parallel]
 - One thread [in omp single] makes tasks [omp task]; other threads handle those tasks automatically as they are created
 - Tasks defined inside omp single are still handled by other threads
 - Original thread will also work on tasks once omp single completes

Memory Models

- Memory models defined in terms of: coherence and consistency
 - *Coherence* - behavior of system when single address is accessed by multiple threads
 - Multiple cores may look at the same value, e.g.
 - *Consistent* - ordering of reads/writes/syncs (RWS) with various addresses, by multiple threads
 - OpenMP shared memory model - all threads share an address space
- Consistency models define constraints on RWS ordering
 - Limit reordering - changes in the order of operations
 - **Sequential consistency** - all operations remain in program order [i.e. order specified in the program]
 - Program order = code [compiled] order = memory commit [machine instruction] order; all processors see the same overall order

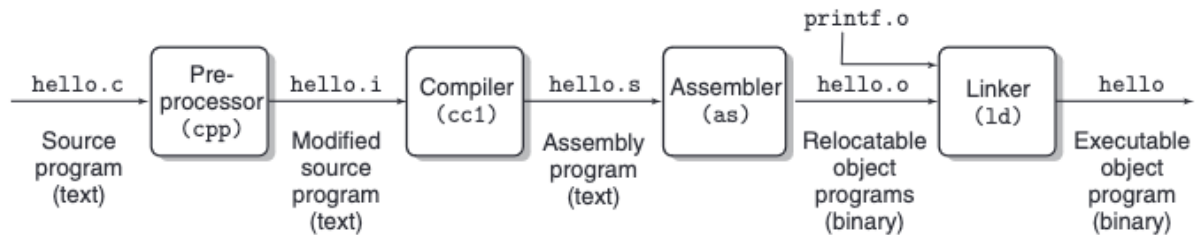
- **Relaxed consistency** removes some of the constraints of sequential
- OpenMP weak consistency - reads/writes to diff addresses can be freely reordered
 - Synchronizations create wall (**memory fence**) - cannot reorder across synchronizations
- **Flush** - defines a sequence point at which a thread is guaranteed to have the same view of memory as a flush set
 - **Flush set** – all thread-visible variables [*flush()*], or just a specified set/list of variables [*omp flush(list)*]
 - Flushes with overlapping flush sets cannot be reordered
 - Flush forces data to be updated in memory, so other threads see most recent value
 - All R/W operations overlapping the flush set must either complete before, or execute after, flush
 - OpenMP synchronizations have implied flushes
 - Entry/exit to parallel regions, barriers, entry/exit to critical regions, setting/unsetting of locks
 - `pragma atomic write`, `pragma atomic read` prevent **race conditions** [only one reads/writes at a time]
- **Threadprivate** - makes global data private to a thread
 - Private vs threadprivate - private masks global variables [private-ness ends once structured block completes], threadprivate preserves global scope within thread [variable remains private for lifetime of thread]
 - `threadprivate(variable)` [variable name]
 - `copyin(variable)` - analogous to `firstprivate`
 - `copyprivate(variable)` - analogous to `lastprivate`

Exceptional Control Flow

- The system: I/O connected to CPU via the system
- Main purpose of **CPU architecture** is to **execute instructions**
 - May be user [application] or kernel instructions
- **Control flow** - sequence of instructions executed by the CPU
 - Mechanisms for changing control flow: jumps and branches, calls and returns
 - **Exceptional control flow** - different events/changes to the system state may warrant changes to the control flow
 - **System state events**: data arrives from disk/network adapter [into memory], program error (e.g. division by zero, invalid memory accesses), user interrupts [C-c], system timer expires, etc.
- **Exception** - transfer of control to the OS kernel in response to some event (i.e. some change in processor state)
 - **Kernel** - memory-resident part of the OS
 - Has system-level view (can access disk, e.g.)
 - Temporarily redirects control from user code to **exception handler** before returning
 - May return to same instruction that was left, or next instruction
 - Built on **exception tables** – array in memory, mapping different exceptions to pointers to code for exception handlers (similar to a jump table)
- **Classes of exceptions**:
 - **Asynchronous exceptions (interrupts)** – caused by events external to the processor, and can occur at any time
 - Indicated by setting processor's interrupt pin
 - Ex: timer interrupt, I/O interrupt from external device (e.g. C-c)
 - **Synchronous exceptions** – caused by events arising from execution of an instruction
 - **Traps** – intentional (programmer-set) exceptions
 - Returns control to next instruction upon resuming
 - Ex: system calls (memory reads/writes, requests to the kernel), breakpoints, special instructions
 - **Faults** – unintentional, but possibly recoverable exceptions
 - Either re-executes faulting instruction, or aborts

- Ex: page faults [accesses to unmapped/protected memory, sigseg faults], protection faults, floating point exceptions
- **Aborts** - unintentional, unrecoverable exceptions; immediately abort the program upon occurring
 - Typically occur as a result of system check failures
 - Certain portions of memory may be shut off; different “unwanted” instructions may be turned off [set read-only]
 - Ex: illegal instructions (OS-unsupported instructions, divides by 0, e.g.), parity errors, machine checks
- **System calls** are calls by a program to system call instructions
 - Are associated with unique ID numbers
 - Ex: read/write/open/close files
- **Page faults** involve attempts to access memory locations not currently on DRAM [in memory]; require kernel copying from disk to memory
 - Also requires OS decide what data to eliminate from memory
 - Returns to and re-executes the faulting instruction upon resolution
 - Invalid memory references result in page faults, but do not have a corresponding place in disc to draw from
 - SIGSEGV – page fault returns signal to user process, signaling abort [fault was not recoverable]

Linking



- Steps of compilation:
 - Preparation
 - Parsing – discerning the meaning of different program tokens (“for”, “while”, etc.)
 - Code generation – conversion of code into machine instructions
 - **Linking** – combination of multiple object files into a single executable file
- Types of linking:
 - **Static linking** – code included during the compilation phase
 - Code from program files are compiled into .o object files
 - Relocatable – contains text and data segments, but have not yet been placed in memory (associated with memory addresses)
 - Linker creates a single fully linked, executable object file from relocatable object files, with all code/data required for the program
 - Has actual text, data segments associated with memory addresses
 - **Dynamic linking** – putting “hooks” to external libraries in compiled executables, rather than actually including the literal code of the libraries
 - Removes the requirement to actually put said external libraries in every program that is compiled
 - Drawback: does not allow for cross-program optimization
- Reasons for linking:
 - **Modularity** - programs can be written as collections of smaller source files, rather than one massive file
 - Can build libraries of common functions (e.g. math, C stdlib)
 - **Efficiency** – can compile different source files separately
 - Dynamic linking saves space relative to static linking
- **Linker functions:**
 - **Symbol resolution** - define and reference **symbols** (global variables/functions)

- Store symbol definitions in object file ***symbol tables***
 - **Symbol table** – an array of structs, containing the name, size, and location of each symbol
 - Are associated with one symbol definition during symbol resolution step of linking
 - **Relocation** – linker merges separate code, data sections into single sections
 - Replaces relative locations of symbols in .o files, with final absolute memory addresses in the executable
 - Updates references to symbols with new positions
- *Types of object files:*
 - **Relocatable object files (.o)** – compiled, but not linked files
 - **Executable object files (a.out default)** – statically linked, executable file
 - **Shared object file (.so)** – special form of relocatable object, can be pulled in dynamically at runtime via dynamic linking
- File contents of different relocatable object files all combined into a single file during the relocation process
 - Contains *headers*, *text* (system code, user functions), *data* (system/program data)
- **Packaging common functions:**
 - **Approach 1** – creating a large source file (.o) containing functions; statically linked into each importing program
 - Inefficient to link a large source file every time
 - **Approach 2** – placing every function in a separate source file (.o), which may be specifically linked
 - More efficient than a single .o, but annoying to program
 - **Approach 3 – static libraries (.a – archive files)** combine a number of relocatable object files within a single index
 - Linker then knows how to individually link archive relocatables into executable as needed
 - Archiver creates static libraries from a set of .o files
 - Statically linked; has all data, instructions needed for execution without pulling from external libraries
 - Downsides:

- Multiple programs using the same archive functions would each need to individually store the instructions (redundant code)
 - Minor changes to system libraries may require explicit relinking of all importing applications
 - **Approach 4 (dynamic linking):** code and data are stored in *shared libraries* are loaded and linked into an application dynamically
 - Static linking process creates only partially linked executable; fully linked executable only created in memory by dynamic linker, later
 - May be loaded and linked at either **load-time** or **run-time**
 - Load/run time: process of loading executable into memory, dynamically linking libraries, and executing
 - Also called dynamic link libraries, DLLs, .so files
- **Library interpositioning** – linking technique allowing programmers to intercept/observe calls to arbitrary functions
 - May occur at compile time, link time, or load/run time
 - Functions:
 - Monitoring/profiling – tracking number of calls to functions + call sites, function arguments
 - Malloc tracing – detecting memory leaks, generating address traces

Virtual Memory

- **Virtual memory** –the “memory” that programs see is not the same as the physical memory of the system (DRAM)
 - Applications do not directly see where their data is stored in memory/on disk
 - Requires translation between virtual, physical addresses, incurring some overhead
 - *Benefits:*
 - Can run the same programs on different systems, including with different memory structures/addressing
 - Can run several applications together without needing to modify them to not overwrite each other’s space
 - *Drawbacks:*
 - Allocation of physical memory may not be perfectly efficient
 - No easy solution for when physical memory runs out
- Virtual memory built on **page tables** – stores **page table entries (PTEs)**, mapping page numbers (virtual addresses, as given by the application) to physical addresses in memory
 - Recall: memory divided into **pages** (chunks of memory)
 - Page size operating system-specific
 - Total memory space = page size * # pages
 - Also contains protection bits (e.g. read-write permission), valid bit (whether address exists in physical memory)
 - Valid bit false results in a **page fault**
 - Page table stored in memory
 - **Page table base register (PTBR)** points to physical page table address for current process
 - Page table may be broken up into levels of page tables, for space efficiency
 - **Memory management unit** contains **translation look-aside buffer** [special cache containing portion of the page table], **page walker** [specialized hardware for traversing/searching levels of a page table]
- Virtual addresses consist of a **virtual page number** and **page offset**
 - Virtual page number essentially acts as an index for the page table
 - **Page offset** - bits for storing offset from initial memory address of page to desired byte within the page

- Offset size = $\log_2(\text{page size})$ [in bits]
 - Virtual page offset (VPO) equal to physical page offset (PPO)
- Virtual page number represents upper bits of a physical address; page offset represents lower bits
- **Steps of page retrieval:**
 - (1) Processor sends virtual address to MMU
 - (2) MMU fetches PTE from page table in memory
 - (3) MMU sends fetched physical address to cache/memory
 - (4) Cache/memory returns the value at that address to the processor
 - *Page faults:* MMU fetches PTE with valid bit false at (2)
 - (3) Handler identifies victim [if dirty, pages out to disk]
 - (4) Handler pages in new page, with help from OS
 - Updates PTE in memory to map to new page
 - (5) Returns to original process, resuming halting instruction
- **Translation look-aside buffer (TLB)** is a special cache/caches in the MMU, containing a portion of the overall page table
 - In the case of a TLB hit, a memory access to the page table is skipped [faster]
- Page tables may be broken up into **multi-level page tables**, where each level points to tables of the next level (and final level contains desired virtual memory-physical memory PTEs)
 - Only first level table needs to be stored in physical memory; can page in other levels of the page table (otherwise stored in secondary storage) as needed
 - Saves space on memory, e.g. in the case of an overly large page table
 - PTEs in a page table may be left unallocated if not needed
 - Virtual address contains indexes for each level of page table

RISC

- Reminder: **Instruction set architecture (ISA)** – part of a computer, serving as an intermediary between hardware and software
- Types of ISA: **CISC** vs **RISC**
 - **Complex instruction-set computers (CISC)** – instruction set supporting a large number of different instructions
 - Efficient memory-wise; initially popular due to the high cost of memory historically (used in x86-64, e.g.)
 - A single instruction may take several cycles to complete
 - **Reduced instruction-set computers (RISC)** – uses simpler set of instructions/operations, allowing for a simpler associated hardware
 - Con: Simple nature of instruction means performing a single task requires more instructions (using more space in memory); a single instruction only takes one cycle to complete
 - Pro: Since instructions are smaller and simpler than CISC, they can be rearranged more easily (e.g. by a compiler) for better optimization
 - Can be parallelized more easily, e.g. (better performance)
 - Essentially breaks up single CISC instructions into sequences of smaller instructions
- **CISC vs RISC:**
 - RISC typically has a larger number of registers than CISC
 - RISC only has one register type, relative to CISC's many
 - Done to minimize number of memory accesses needed, for performance
 - RISC architectures do not allow for taking memory addresses as arithmetic operands (must perform load, arithmetic operation in separate instructions)
 - RISC architectures have three-address instructions, where CISC have two
 - CISC has variable-length instructions; RISC originally only supported 32-bit
- Misc:
 - Pipelining (performing different operations simultaneously) vs parallelism (performing the same operation multiple times simultaneously)
 - Intel gradually moving from CISC to RISC

- x86-64 is built on CISC, but has been trying to avoid using more complex instructions (i.e. use more RISC-like instructions)
- ARM built on RISC
- CISC vs RISC is not a clear line
 - RISC originally only had one size of instruction (32-bit); has been branching out into supporting different types of instructions (e.g. 16-bit)
 - Has introduced macro op fusion to fuse instructions into more complex instructions
- Fixed-length vs variable-length instructions
 - Fixed-length is easier to decode (can always read the same number of bytes), but less space-efficient (cannot make smaller instructions, even if the full length results in wasted space)
 - Is notably also less susceptible to code injection with gadgets (cannot splice into the middle of an instruction as easily, e.g.)

MIPS

- **MIPS** – basic RISC architecture
 - Words 4 bytes in memory; aligned at multiples of 4
 - Is a *load-store architecture*: every operand of a MIPS instruction must be in a register [generally speaking]
 - Requires explicit data movement (i.e. explicit loads, stores), as opposed to x86's memory-addressing operands (e.g. 8(%rax))
 - Only a few basic operations
 - Instruction format: INST DEST, SRC1, SRC2
 - Convention: **rd** = destination register, **rs** = source register, **rt** = source or destination register (depending on instruction), **immed** = a 16-bit value
- MIPS registers specified with \$; can be specified by register number or by name
 - MIPS has 32 32-bit registers for general operations; 32 for floating-point
 - Temporary registers: \$t0 - \$t9
 - Callee-saved registers: \$s0 - \$s3

- Also contains 32-bit program counter (PC), registers HI and LO for multiplication/division, other special-purpose registers
 - \$0 (\$zero) always holds the value zero (can be specified with 5-bit register name rather than 32-bit integer value, for compactness)
- Only a few types of MIPS instructions: **R[egister]**, **I[mmediate]**, **J[ump]**
 - **R-type instructions:** 6-bit opcode; 5-bits each for RS, RT, RD; 5-bit shift amount (used for shift instructions); 6-bit func field
 - All R-types use the same 6-bit opcode (all 0s); store actual function encoding in 6-bit func field
 - Allows for $2^6 - 1$ different I/J instructions (denoted by opcode) + 2^6 different R instructions (denoted by func)
 - **I-type:** 6-bit opcode, 5-bits for RS, RT; 16-bits for immediate
 - **J-type:** 6-bit opcode, 26-bit immediate (used for jumps)

MIPS Instructions

- MIPS relies on explicit load/store instructions (**LW** = *loadword*/**SW** = *storeword* read from/write to memory, respectively, e.g.)
 - LW is I-format: LW RT, IMMED(RS) places value of IMMED(RS) into RT
 - Memory address to be read represented as value of RS + sign-extended immediate [displacement]
 - SW: SW RT, IMMED(RS) stores RT at IMMED(RS)
 - Memory address to be stored into represented as value of RS + sign-extended immediate
- Arithmetic operations: ADD vs ADDI [*add immediate*], sub
 - ADD: ADD rd, rs, rt vs ADDI: ADDI rt, rs, immed
 - R-type: R[RS] FUNC R[RT] -> R[RD]
 - ADDIU [add unsigned immediate]
 - No single analogous LEAQ instruction
 - addu \$s7, \$0, \$ra – push return address to \$s7
- Branching: BEQ (branch equal) and BNE (branch not equal)
 - Branching: BEQ rs, rt, target [target representing some address or label in memory], change program counter on jump

- Comparison instructions: SLT (set less than) + SLTU (set less than [unsigned])
 - SLT: SLT rd, rs, rt (set rd to 1 if true (rs < rt), 0 if false)
- Jump instructions are unconditional
 - J target [jump to target], JR rs [jump to target stored in register]
 - JAL [jump and link] used to call procedures; JR \$31 [jump to return address] for returning from procedures
 - JAL: JAL target jumps to target; stores value of PC [return address, essentially] + 4 [next instruction] in \$31
 - JALR: JALR rs, rd jumps to address in rs; stores value of rd in \$31
- Logic: AND, OR, XOR [+I]
 - Immed constant limited to 16 bits – LUI loads constant to upper bits of a register
- Pseudo-instructions: instructions available in assembly, but eventually broken down into series of simpler instructions in machine code
 - Move, clear, li [load 16-bit/32-bit immediate], la [load label address: la \$t, A]
- Syscalls: print/read integers and strings [from memory; address as input]; exit/end program
- MIPS instructions also stored in text, global segments
 - .text – defines where program is stored
 - .global __start: calls start function in global scope
 - __start: defines start function (label)
 - Can label strings (e.g str: .asciiz "hi"), use label (str) when referring to memory addresses (with la, e.g.) in assembly