CS 61C: Great Ideas in Computer Architecture

OpenMP, Transistors

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Review of Last Lecture

- Amdahl’s Law limits benefits of parallelization
- Multiprocessor systems uses shared memory (single address space)
- Cache coherence implements shared memory even with multiple copies in multiple caches
  - Track state of blocks relative to other caches (e.g. MOESI protocol)
  - False sharing a concern
- Synchronization via hardware primitives:
  - MIPS does it with Load Linked + Store Conditional

Question: Consider the following code when executed *concurrently* by two threads.

What possible values can result in *($s0)?

```
# *($s0) = 100
lw   $t0,0($s0)
addi $t0,$t0,1
sw   $t0,0($s0)
```

(B) **101 or 102**

(G) **100, 101, or 102**

(P) **100 or 101**

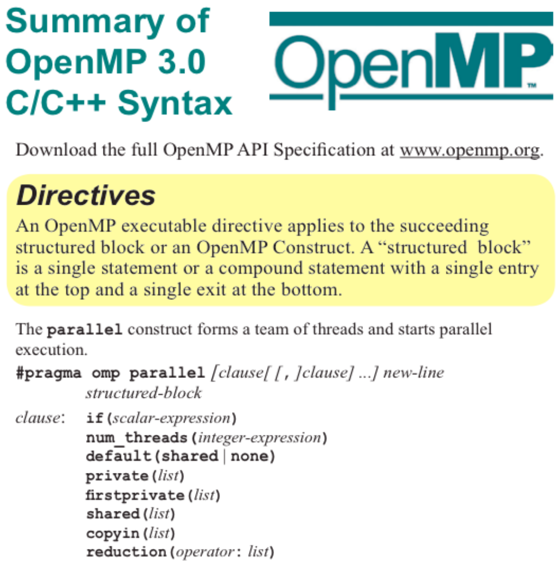
(Y) **102**

Agenda

- OpenMP Introduction
- Administrivia
- OpenMP Directives
  - Workshare
  - Synchronization
- OpenMP Common Pitfalls
- Hardware: Transistors

What is OpenMP?

- API used for multi-threaded, shared memory parallelism
  - Compiler Directives
  - Runtime Library Routines
  - Environment Variables
- Portable
- Standardized



Summary of OpenMP 3.0 C/C++ Syntax

Download the full OpenMP API Specification at www.openmp.org.

Directives

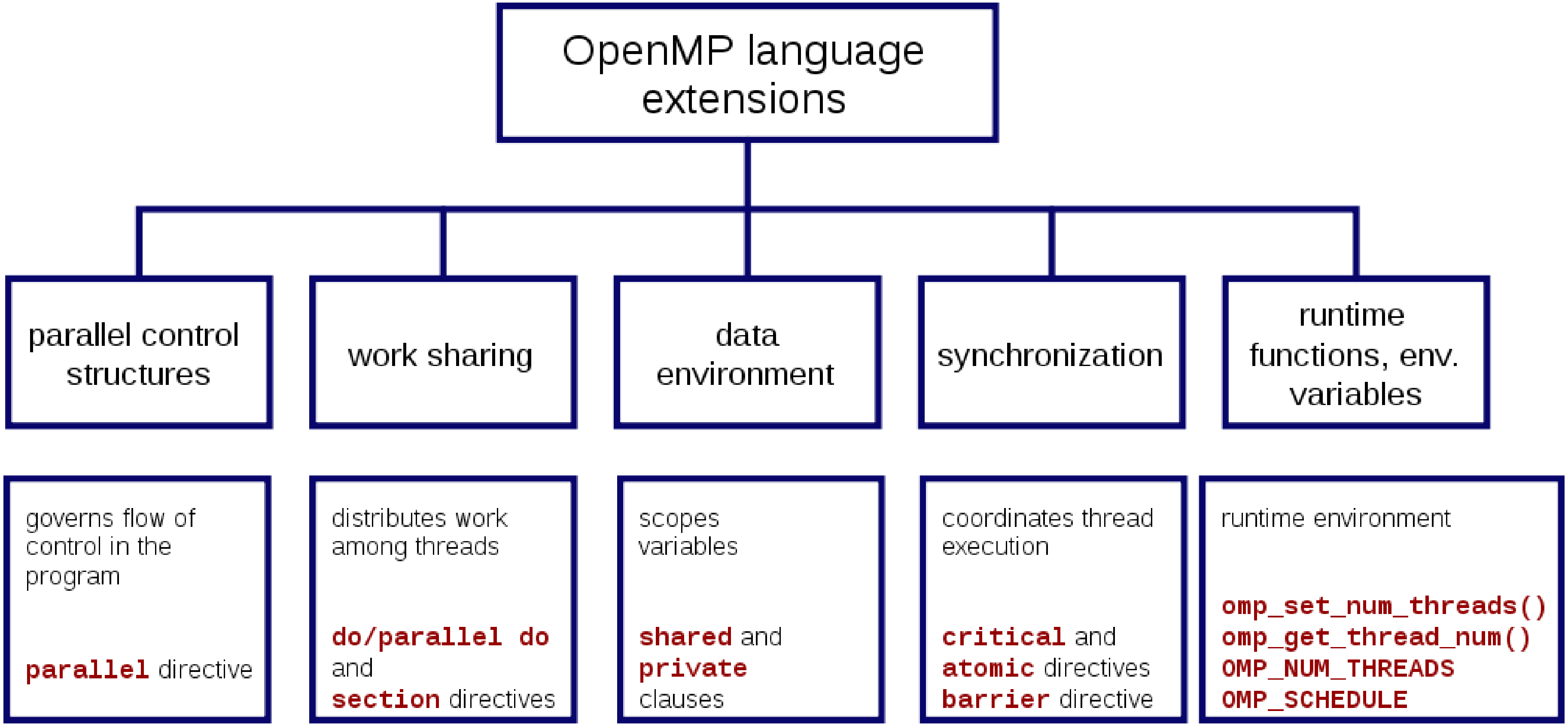
An OpenMP executable directive applies to the succeeding structured block or an OpenMP Construct. A "structured block" is a single statement or a compound statement with a single entry at the top and a single exit at the bottom.

The **`parallel`** construct forms a team of threads and starts parallel execution.

```
#pragma omp parallel [clause[ [, ]clause] ...] new-line
          structured-block
clause:   if (scalar-expression)
          num_threads (integer-expression)
          default (shared | none)
          private (list)
          firstprivate (list)
          shared (list)
          copyin (list)
          reduction (operator: list)
```

- **Resources:** http://www.openmp.org/ and http://computing.llnl.gov/tutorials/openMP/

OpenMP Specification



OpenMP language extensions

parallel control structures

work sharing

data environment

synchronization

runtime functions, env. variables

governs flow of control in the program

`parallel` directive

distributes work among threads

`do/parallel do` and **`section`** directives

scopes variables

`shared` and **`private`** clauses

coordinates thread execution

`critical` and **`atomic`** directives **`barrier`** directive

runtime environment

`omp_set_num_threads()`
`omp_get_thread_num()`
`OMP_NUM_THREADS`
`OMP_SCHEDULE`

Shared Memory Model with Explicit Thread-based Parallelism

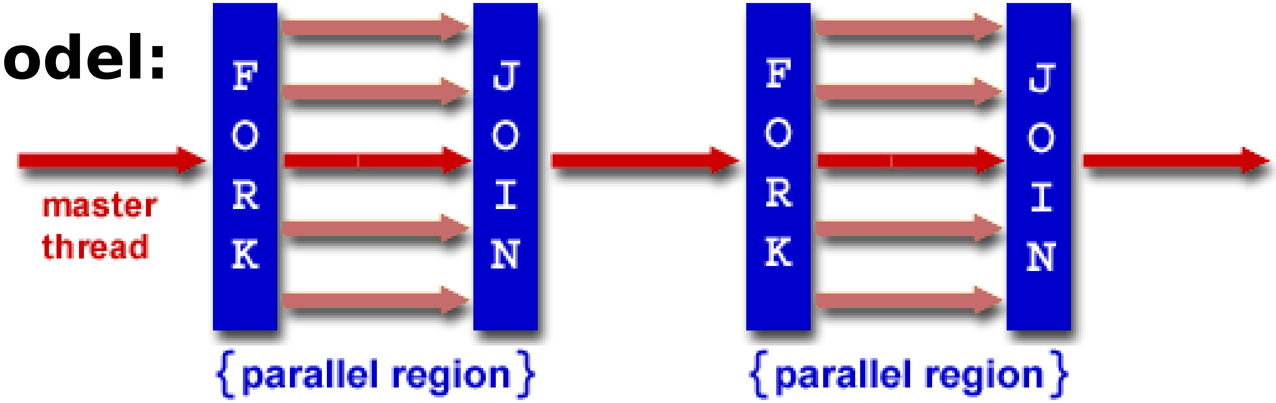
- Multiple threads in a shared memory environment, explicit programming model with full programmer control over parallelization
- **Pros:**
  - Takes advantage of shared memory, programmer need not worry (that much) about data placement
  - Compiler directives are simple and easy to use
  - Legacy serial code does not need to be rewritten
- **Cons:**
  - Code can only be run in shared memory environments
  - Compiler must support OpenMP (e.g. gcc 4.2)

OpenMP in CS61C

- OpenMP is built on top of C, so you don't have to learn a whole new programming language
  - Make sure to add `#include <omp.h>`
  - Compile with flag: `gcc -fopenmp`
  - Mostly just a few lines of code to learn
- You will NOT become experts at OpenMP
  - Use slides as reference, will learn to use in lab
- **Key ideas:**
  - Shared vs. Private variables
  - OpenMP directives for parallelization, work sharing, synchronization

OpenMP Programming Model

- **Fork - Join Model:**



  - OpenMP programs begin as single process (*master thread*) and executes sequentially until the first parallel region construct is encountered
    - *FORK:* Master thread then creates a team of parallel threads
    - Statements in program that are enclosed by the parallel region construct are executed in parallel among the various threads
    - *JOIN:* When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

OpenMP Extends C with Pragmas

- *Pragmas* are a preprocessor mechanism C provides for language extensions
- Commonly implemented pragmas:
  structure packing, symbol aliasing, floating point exception modes (not covered in 61C)
- Good mechanism for OpenMP because compilers that don't recognize a pragma are supposed to ignore them
  - Runs on sequential computer even with embedded pragmas

`parallel` Pragma and Scope

- Basic OpenMP construct for parallelization:

```
#pragma omp parallel
{
/* code goes here */
}
```

This is annoying, but curly brace MUST go on separate line from #pragma

  - *Each* thread runs a copy of code within the block
  - Thread scheduling is *non-deterministic*
- Variables declared outside pragma are *shared*
  - To make private, need to declare with pragma:

```
#pragma omp parallel private (x)
```

Thread Creation

- Defined by OMP_NUM_THREADS environment variable (or code procedure call)
  - Set this variable to the *maximum* number of threads you want OpenMP to use
- Usually equals the number of cores in the underlying hardware on which the program is run
  - But remember thread ≠ core

OMP_NUM_THREADS

- OpenMP intrinsic to set number of threads:

```
omp_set_num_threads(x);
```

- OpenMP intrinsic to get number of threads:

```
num_th = omp_get_num_threads();
```

- OpenMP intrinsic to get Thread ID number:

```
th_ID = omp_get_thread_num();
```

Parallel Hello World

```
#include <stdio.h>
#include <omp.h>
int main () {
  int nthreads, tid;
  /* Fork team of threads with private var tid */
  #pragma omp parallel private(tid)
  {
    tid = omp_get_thread_num(); /* get thread id */
    printf("Hello World from thread = %d\n", tid);
    /* Only master thread does this */
    if (tid == 0) {
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
    }
  }  /* All threads join master and terminate */
}
```

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Administrivia

- Midterm Grades by this sunday
  - Using pandagrader, make sure your registered email is accurate
  - Slower initial grading, faster regrades
- Project 2: Eigenvector Finding Performance Improvement
  - Part 1: Due this Sunday
    - Just need to find a partner

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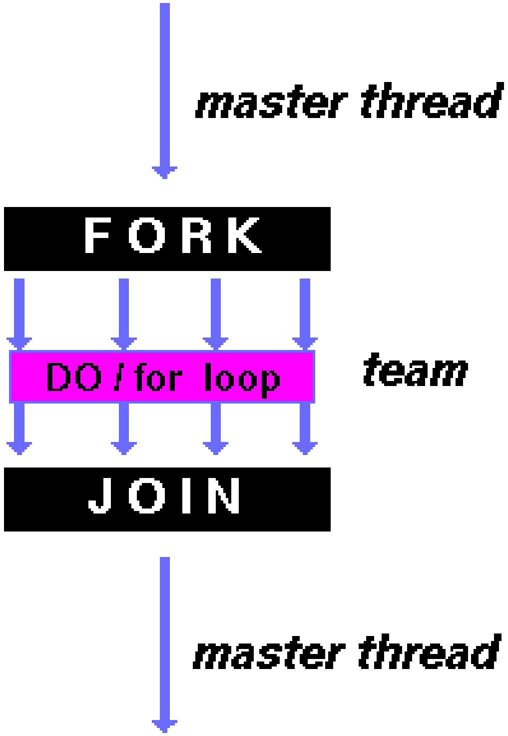
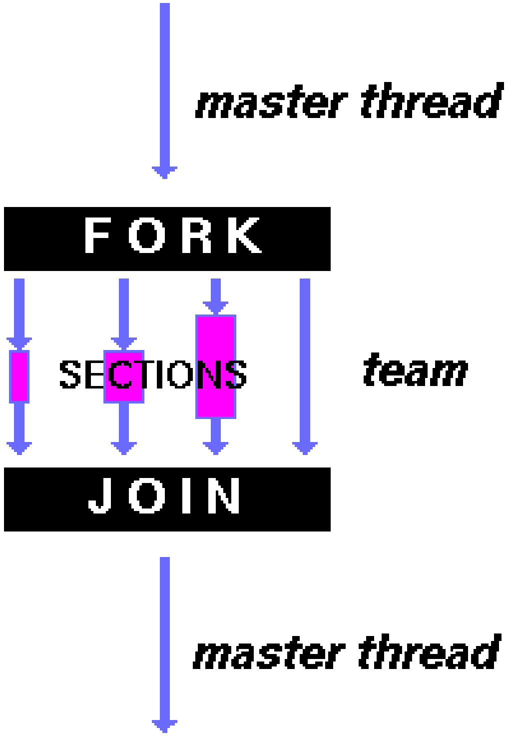
OpenMP Directives (Work-Sharing)

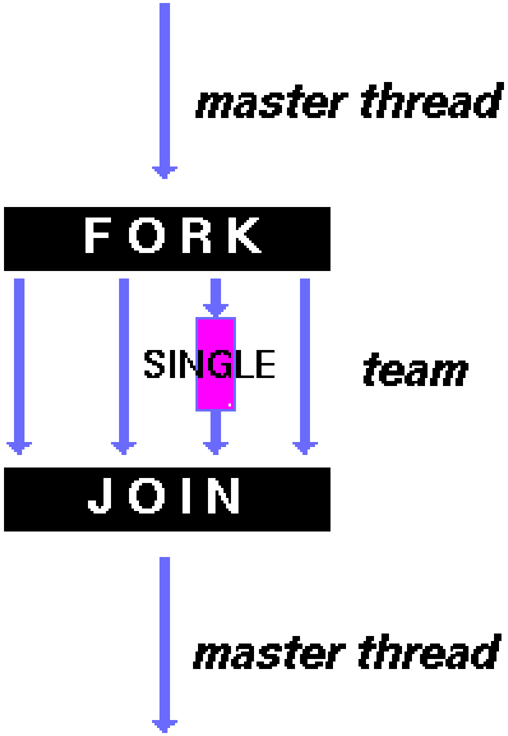
- These are defined *within* a `parallel` section



Shares iterations of a loop across the threads



Each section is executed by a separate thread



Serializes the execution of a thread

Parallel Statement Shorthand

```
#pragma omp parallel
{
  #pragma omp for
  for(i=0; i<len; i++) { … }
}
```

This is the only directive in the parallel section

can be shortened to:

```
#pragma omp parallel for
  for(i=0; i<len; i++) { … }
```

Building Block: `for loop`

`for (i=0; i<max; i++) zero[i] = 0;`

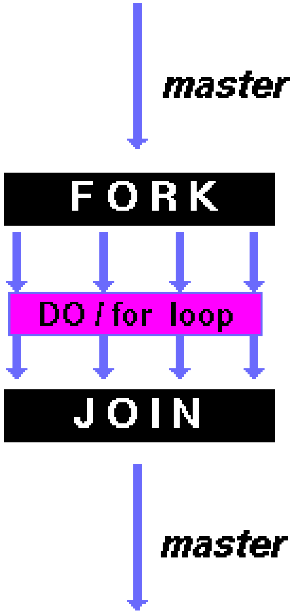
- Break *for loop* into chunks, and allocate each to a separate thread
  - e.g. if `max` = 100 with 2 threads:
    assign 0-49 to thread 0, and 50-99 to thread 1
- Must have relatively simple "shape" for an OpenMP-aware compiler to be able to parallelize it
  - Necessary for the run-time system to be able to determine how many of the loop iterations to assign to each thread
- No premature exits from the loop allowed
  - i.e. No `break`, `return`, `exit`, `goto` statements

In general, don't jump outside of any pragma block

Parallel `for` *pragma*

```
#pragma omp parallel for
  for (i=0; i<max; i++) zero[i] = 0;
```

- Master thread creates additional threads, each with a separate execution context
  - Implicit synchronization at end of for loop
- Loop index variable (i.e. `i`) made *private*
- Divide index regions sequentially per thread
  - Thread 0 gets 0, 1, …, (max/n)-1;
  - Thread 1 gets max/n, max/n+1, …, 2*(max/n)-1



OpenMP Timing

- Elapsed wall clock time:

  `double omp_get_wtime(void);`

  - Returns elapsed wall clock time in seconds
  - Time is measured per thread, no guarantee can be made that two distinct threads measure the same time
  - Time is measured from "some time in the past," so subtract results of two calls to `omp_get_wtime` to get elapsed time

Matrix Multiply in OpenMP

```
start_time = omp_get_wtime();
#pragma omp parallel for private(tmp, i, j, k)
  for (i=0; i<Mdim; i++){
    for (j=0; j<Ndim; j++){
      tmp = 0.0;
      for( k=0; k<Pdim; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += *(A+(i*Pdim+k)) * *(B+(k*Ndim+j));
      }
      *(C+(i*Ndim+j)) = tmp;
    }
  }
run_time = omp_get_wtime() - start_time;
```

Outer loop spread across N threads; inner loops inside a single thread

Notes on Matrix Multiply Example

- More performance optimizations available:
  - Higher *compiler optimization* (-O2, -O3) to reduce number of instructions executed
  - *Cache blocking* to improve memory performance
  - Using SIMD SSE instructions to raise floating point computation rate (*DLP*)
  - Improve algorithm by reducing computations and memory accesses in code (what happens in each loop?)

OpenMP Directives (Synchronization)

- These are defined *within* a `parallel` section
- `master`
  - Code block executed only by the master thread (all other threads skip)
- `critical`
  - Code block executed by only one thread at a time
- `atomic`
  - Specific memory location must be updated atomically (like a mini-`critical` section for writing to memory)
  - Applies to single statement, not code block

OpenMP Reduction

- *Reduction* specifies that one or more private variables are the subject of a reduction operation at end of parallel region
  - Clause `reduction(operation:var)`
  - *Operation:* Operator to perform on the variables at the end of the parallel region
  - *Var:* One or more variables on which to perform scalar reduction

```
#pragma omp for reduction(+:nSum)
  for (i = START ; i <= END ; i++)
    nSum += i;
```

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OpenMP Pitfall #1: Data Dependencies

- Consider the following code:

```
a[0] = 1;
for(i=1; i<5000; i++)
  a[i] = i + a[i-1];
```

  - There are dependencies between loop iterations!
    - Splitting this loop between threads does not guarantee in-order execution
    - Out of order loop execution will result in nondeterministic behavior (i.e. likely wrong result)

Open MP Pitfall #2: Sharing Issues

- Consider the following loop:

```
#pragma omp parallel for
   for(i=0; i<n; i++){
      temp = 2.0*a[i];
      a[i] = temp;
      b[i] = c[i]/temp;
   }
```

- temp is a shared variable!

```
#pragma omp parallel for private(temp)
   for(i=0; i<n; i++){
      temp = 2.0*a[i];
      a[i] = temp;
      b[i] = c[i]/temp;
   }
```

OpenMP Pitfall #3: Updating Shared Variables Simultaneously

- Now consider a global sum:

```
#pragma omp parallel for
    for(i=0; i<n; i++)
        sum = sum + a[i];
```

  - This can be done by surrounding the summation by a `critical`/`atomic` section or `reduction` clause:

```
#pragma omp parallel for reduction(+:sum)
    for(i=0; i<n; i++)
        sum = sum + a[i];
```

    - Compiler can generate highly efficient code for `reduction`

OpenMP Pitfall #4: Parallel Overhead

- Spawning and releasing threads results in significant overhead
- Better to have fewer but larger parallel regions
  - Parallelize over the largest loop that you can (even though it will involve more work to declare all of the private variables and eliminate dependencies)

OpenMP Pitfall #4: Parallel Overhead

```
start_time = omp_get_wtime();
for (i=0; i<Mdim; i++){
  for (j=0; j<Ndim; j++){
    tmp = 0.0;
    #pragma omp parallel for reduction(+:tmp)
      for( k=0; k<Pdim; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += *(A+(i*Pdim+k)) * *(B+(k*Ndim+j));
      }
    *(C+(i*Ndim+j)) = tmp;
  }
}
run_time = omp_get_wtime() - start_time;
```

Too much overhead in thread generation to have this statement run this frequently.

Poor choice of loop to parallelize.

Technology Break

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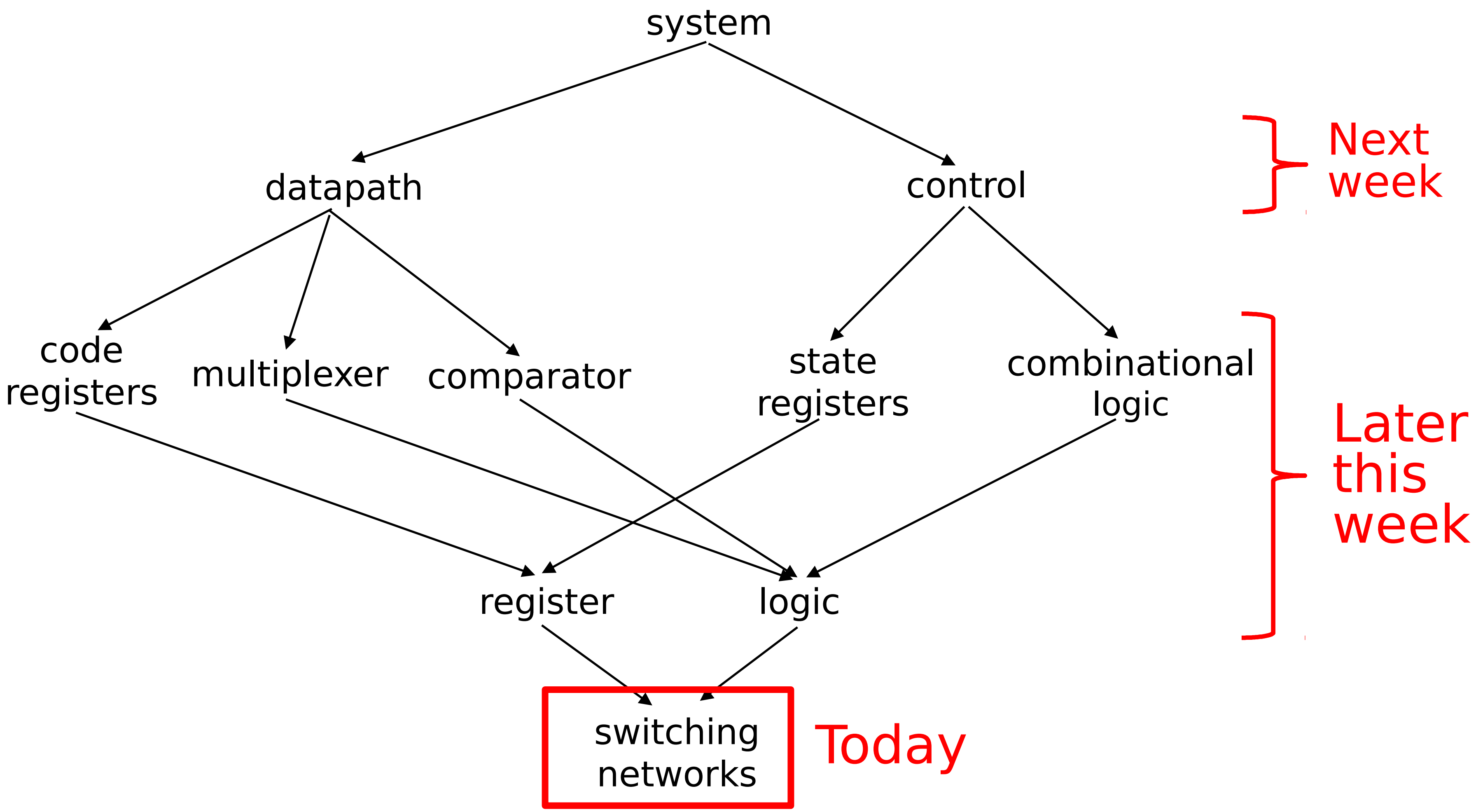
Hardware Design

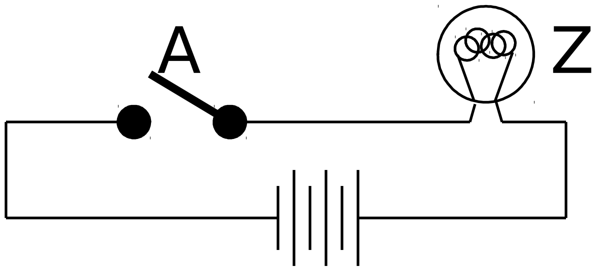
- **Upcoming:** We’ll study how a modern processor is built, starting with basic elements as building blocks
- Why study hardware design?
  - Understand capabilities and limitations of hardware in general and processors in particular
  - What processors can do fast and what they can’t do fast (avoid slow things if you want your code to run fast!)
  - Background for more in-depth courses (CS150, CS152)
  - You may need to design own custom hardware for extra performance (some commercial processors today have customizable hardware)

Design Hierarchy

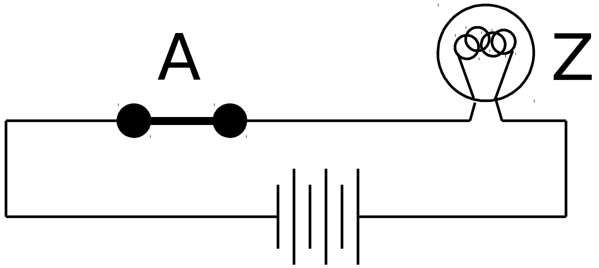


Switches (1/2)

- The basic element of physical implementations
- Convention: if input is a “1,” the switch is *asserted*



Open switch if A is “0” (unasserted) and turn OFF light bulb (Z)

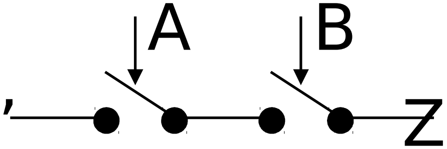


Close switch if A is “1” (asserted) and turn ON light bulb (Z)

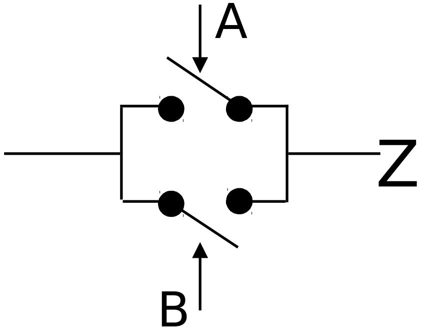
In this example, $Z \equiv A$.

Switches (2/2)

- Can compose switches into more complex ones (Boolean functions)
  - Arrows show action upon assertion (1 = close)



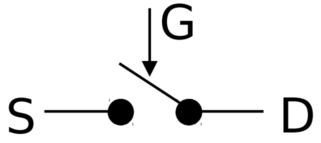
AND: “1” Z ≡ A and B



OR: “1” Z ≡ A or B

Transistor Networks

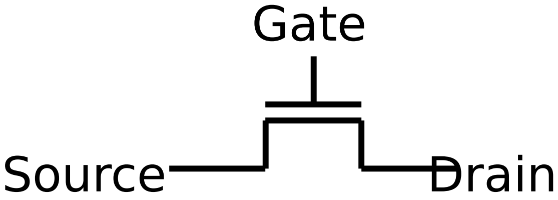
- Modern digital systems designed in CMOS
  - MOS: Metal-Oxide on Semiconductor
  - C for *complementary*: use pairs of normally-open and normally-closed switches
- CMOS transistors act as voltage-controlled switches
  - Similar, though easier to work with, than relay switches from earlier era
  - Three terminals: **S**ource, **G**ate, and **D**rain



CMOS Transistors

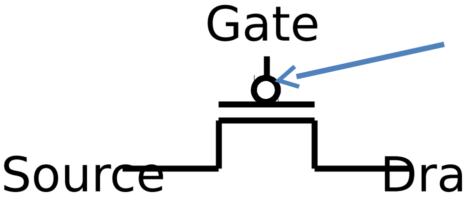
- Switch action based on terminal voltages (VG, VD, VS) and *relative* voltages (e.g. VGS, VDS)
  - Threshold voltage (VT) determines whether or not Source and Drain terminals are connected
  - When not connected, Drain left “floating”

N-channel Transistor



VG–VS < VT: Switch OPEN
VGS–VDS > VT: Switch CLOSED

P-channel Transistor

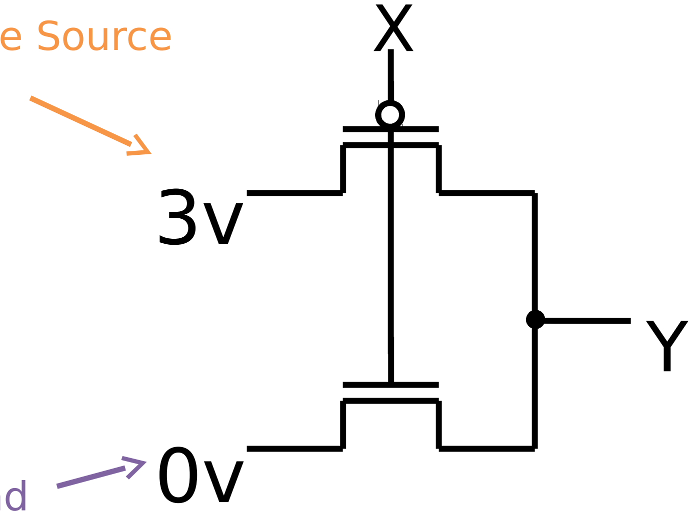


Circle symbol means “NOT” or “complement”

VS–VG < -VT: Switch CLOSED
VSG–VSD > -VT: Switch OPEN

MOS Networks

- What is the relationship between X and Y?



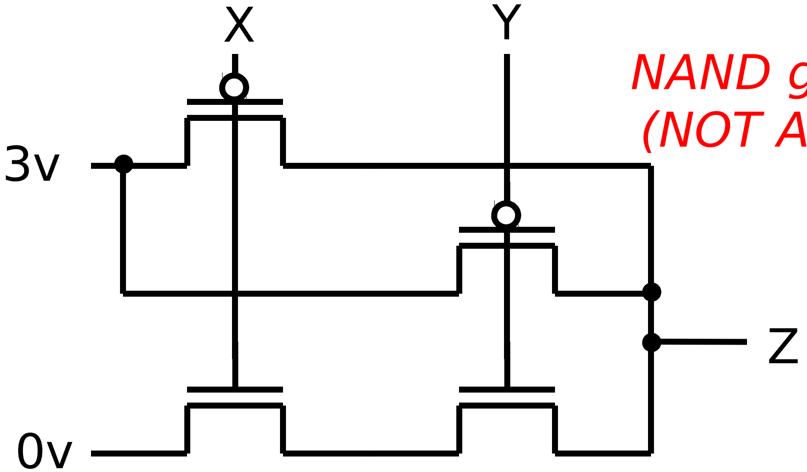
Voltage Source ("1")

Ground ("0")

X	**Y**
-3 V	+3 V
+3 V	+0 V

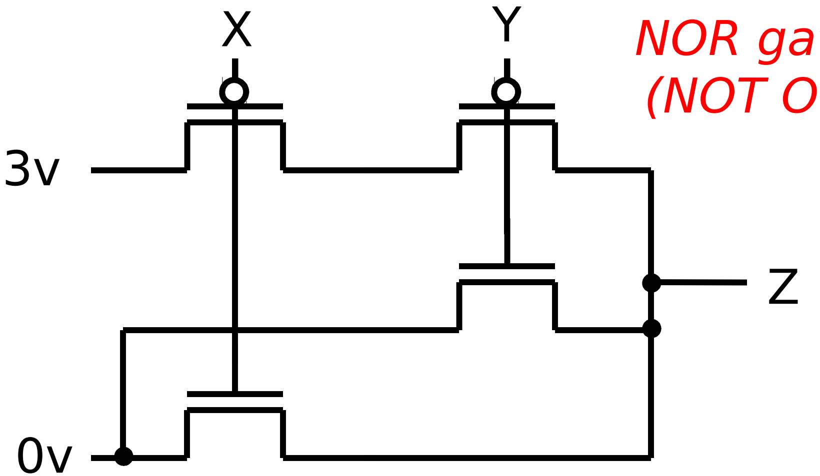
Called an inverter or NOT gate

Two Input Networks



NAND gate
(NOT AND)

X	Y	Z
-3 V	-3 V	+3 V
-3 V	+3 V	+3 V
+3 V	-3 V	+3 V
+3 V	+3 V	+0 V



NOR gate
(NOT OR)

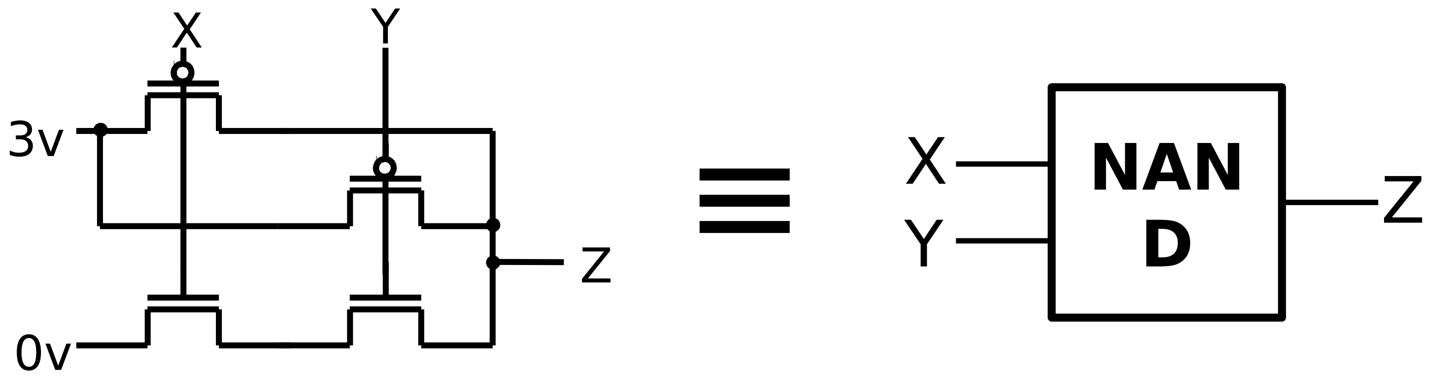
X	Y	Z
-3 V	-3 V	+3 V
-3 V	+3 V	+0 V
+3 V	-3 V	+0 V
+3 V	+3 V	+0 V

Transistors and CS61C

- The internals of transistors are important, but won’t be covered in this class
  - Better understand Moore’s Law
  - Physical limitations relating to speed and power consumption
  - Actual physical design & implementation process
  - Can take EE40, EE105, and EE140
- We will proceed with the abstraction of *Digital Logic* (0/1)

Block Diagrams

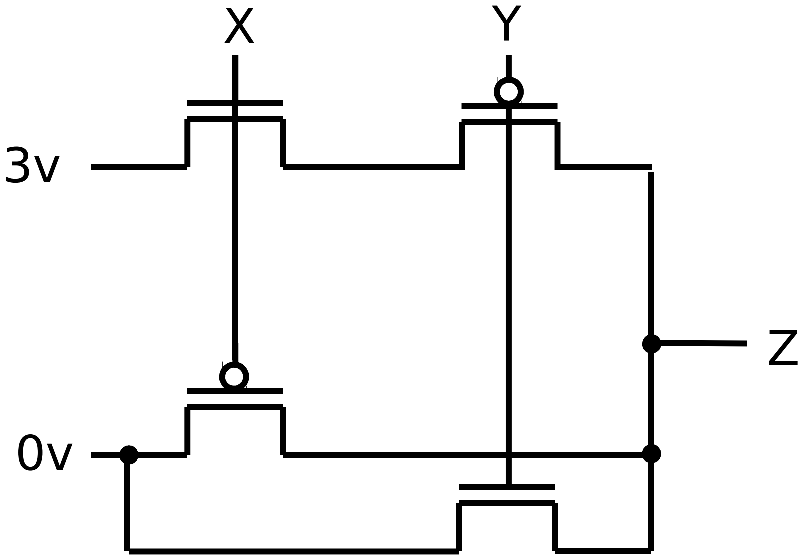
- In reality, chips composed of just transistors and wires
  - Small groups of transistors form useful building blocks, which we show as *blocks*



- Can combine to build higher-level blocks
  - You can build AND, OR, and NOT out of NAND!

Question: Which set(s) of inputs will result in the output Z being 3 volts?

Using digital logic – “0” is -3 V, “1” is +3 V



	X	**Y**
(B)	**0**	**0**
(G)	**0**	**1**
(P)	**1**	**0**
(Y)	**1**	**1**

Summary

- OpenMP as simple parallel extension to C
  - During parallel fork, be aware of which variables should be shared vs. private among threads
  - Work-sharing accomplished with for/sections
  - Synchronization accomplished with critical/atomic/reduction
- Hardware is made up of transistors and wires
  - Transistors are voltage-controlled switches
  - Building blocks of all higher-level blocks