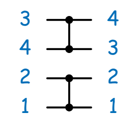
Lecture 32: Parallelism

- Moore's law ("Transistors per chip doubles every N years"), where N is roughly 2 (about $1,000,000\times$ increase since 1971).
- Has also applied to processor speeds (doubling a bit faster).
- But predicted to flatten: further increases to be obtained through *parallel processing* (witness: multicore/manycode processors).
- With distributed processing, issues involve interfaces, reliability, communication issues.
- With other parallel computing, where the aim is performance, issues involve synchronization, balancing loads among processors, and, yes, "data choreography" and communication costs.

Example of Parallelism: Sorting

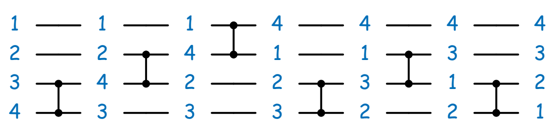
- Sorting a list presents obvious opportunities for parallelization.
- Can illustrate various methods diagrammatically using *comparators* as an elementary unit:



- Each vertical bar represents a *comparator*—a comparison operation or hardware to carry it out—and each horizontal line carries a data item from the list.
- A comparator compares two data items coming from the left, swapping them if the lower one is larger than the upper one.
- Comparators can be grouped into operations that may happen simultaneously; they are always grouped if stacked vertically as in the diagram.

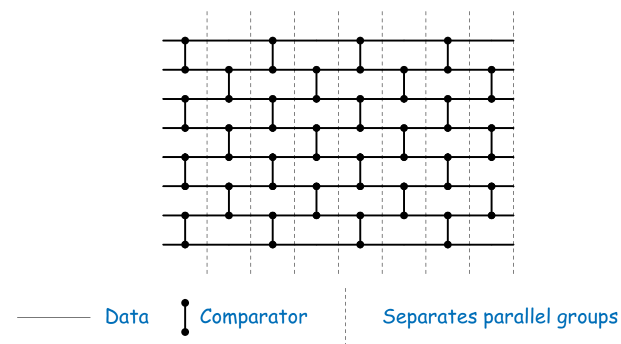
Sequential sorting

- Here's what a sequential sort (selection sort) might look like:

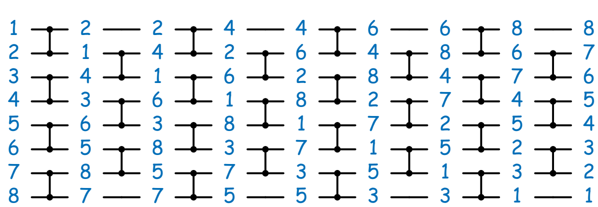


- Each comparator is a separate operation in time.
- In general, there will be $\Theta(N^2)$ steps.
- But since some comparators operate on distinct data, we ought to be able to overlap operations.

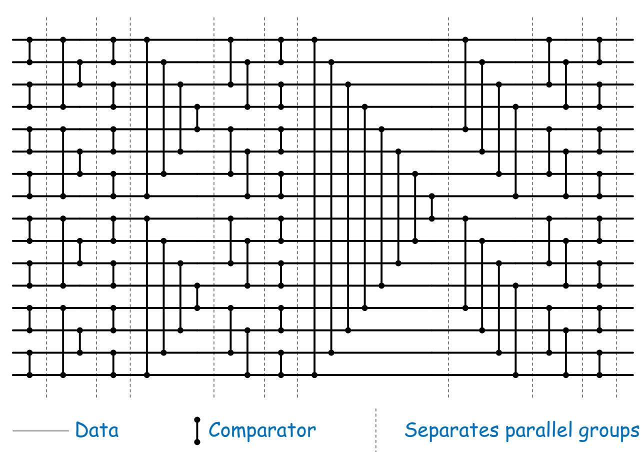
Odd-Even Transposition Sorter



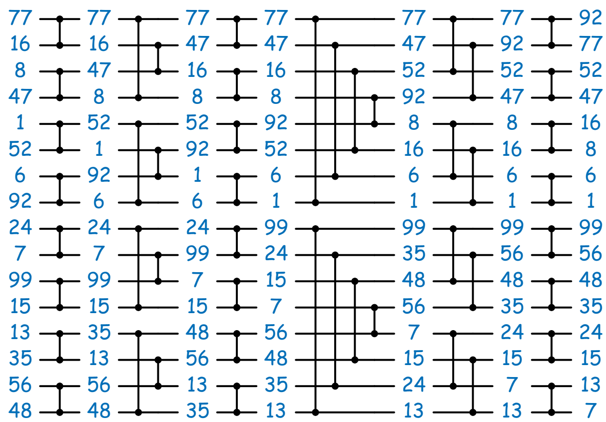
Odd-Even Sort Example



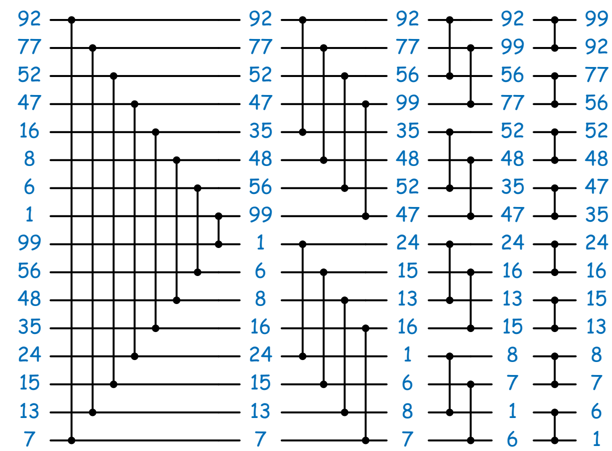
Example: Bitonic Sorter



Bitonic Sort Example (I)



Bitonic Sort Example (II)



Implementing Parallel Programs

- The sorting diagrams were abstractions.
- Comparators could be processors, or they could be operations divided up among one or more processors.
- Coordinating all of this is the issue.
- One approach is to use *shared memory*, where multiple processors (logical or physical) share one memory.
- This introduces conflicts in the form of *race conditions:* processors racing to access data.

Memory Conflicts: Abstracting the Essentials

- When considering problems relating to shared-memory conflicts, it is useful to look at the primitive read-to-memory and write-to-memory operations.
- E.g., the program statements on the left cause the actions on the right.

```
x = 5                   WRITE 5 -> x
x = square(x)           READ x -> 5
                        (calculate 5*5 -> 25)
                        WRITE 25 -> x
y = 6                   WRITE 6 -> y
y += 1                  READ y -> 6
                        (calculate 6+1 -> 7)
                        WRITE 7 -> y
```


Conflict-Free Computation

- Suppose we divide this program into two separate processes, P1 and P2:

`x = 5` `x = square(x)`	`y = 6` `y += 1`
P1	P2

`WRITE 5 -> x`
`READ x -> 5`
`(calculate 5*5 -> 25)`
`WRITE 25 -> x`
	`WRITE 6 -> y`
	`READ y -> 6`
	`(calculate 6+1 -> 7)`
	`WRITE 7 -> y`

```
x = 25
y = 7
```

- The result will be the same regardless of which process's READs and WRITEs happen first, because they reference different variables.

Read-Write Conflicts

- Suppose that both processes read from `x` after it is initialized.

`x = 5`

`x = square(x)`	`y = x + 1`
P1	P2

`READ x -> 5`
`(calculate 5*5 -> 25)`
`WRITE 25 -> x`
`|`
	`|`
	`READ x -> 5`
	`(calculate 5+1 -> 6)`
	`WRITE 6 -> y`

```
x = 25
y = 6
```

- The statements in `P2` must appear in the given order, but they need not line up like this with statements in `P1`, because the execution of `P1` and `P2` is independent.

Read-Write Conflicts (II)

- Here's another possible sequence of events

x = 5

x = square(x)	y = x + 1

P1	P2
READ x -> 5	|
(calculate 5*5 -> 25)	|
WRITE 25 -> x	|
|	READ x -> 25
|	(calculate 25+1 -> 26)
|	WRITE 26 -> y

x = 25
y = 26

Read-Write Conflicts (III)

- The problem here is that nothing forces P1 to wait for P1 to read x before setting it.
- Observation: The "calculate" lines have no effect on the outcome. They represent actions that are entirely local to one processor.
- The effect of "computation" is simply to delay one processor.
- But processors are assumed to be delayable by many factors, such as time-slicing (handing a processor over to another user's task), or processor speed.
- So the effect of computation adds nothing new to our simple model of shared-memory contention that isn't already covered by allowing any statement in one process to get delayed by any amount.
- So we'll just look at READ and WRITE in the future.

Write-Write Conflicts

- Suppose both processes write to x:

x = 5

x = square(x)	x = x + 1

P1	P2
|	READ x -> 5
READ x -> 5	|
|	WRITE 6 -> x
|	|
WRITE 25 -> x	

x = 25

- This is a *write-write conflict:* two processes race to be the one that "gets the last word" on the value of x.

Write-Write Conflicts (II)

x = 5

x = square(x)	x = x + 1

P1	P2
|	READ x -> 5
READ x -> 5	|
WRITE 25 -> x	|
|	WRITE 6 -> x

x = 26

- This ordering is also possible; P2 gets the last word.
- There are also read-write conflicts here. What is the total number of possible final values for x? Four: 25, 5, 26, 36