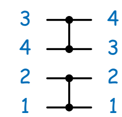
Lecture 33: Concurrency

- 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 (with a different exponent).
- 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

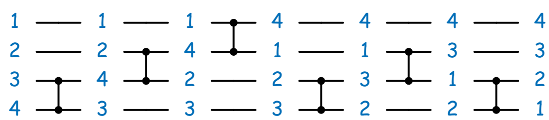
- Sorting a list presents obvious opportunities for parallelization.
- Can illustrate various methods diagrammatically using *comparators* as an elementary unit:



- 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.

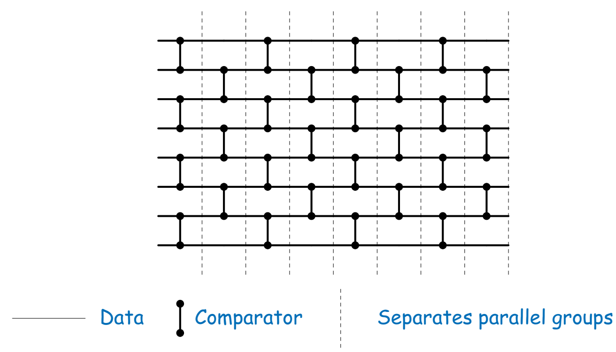
Sequential sorting

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

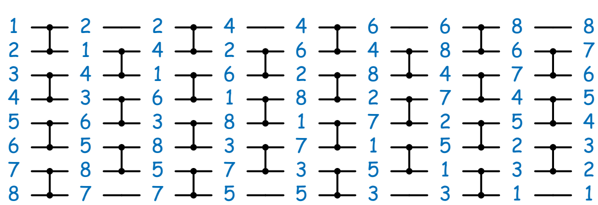


- Each comparator is a separate operation in time.
- In general, there will be $\Theta(N^2)$ steps.
- But since some comparators operate on distinct data, we ought to be able to overlap operations.

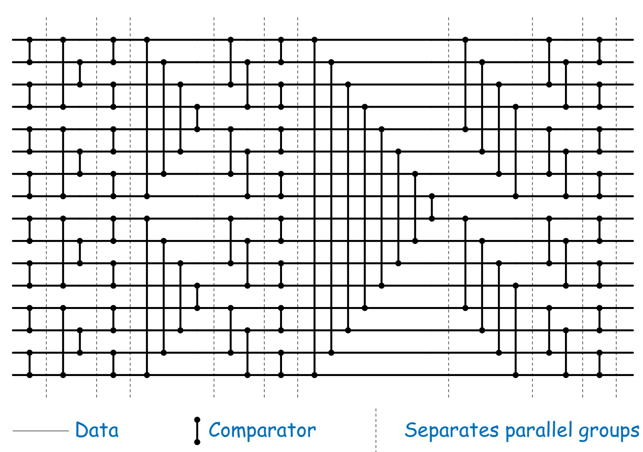
Odd-Even Transposition Sorter



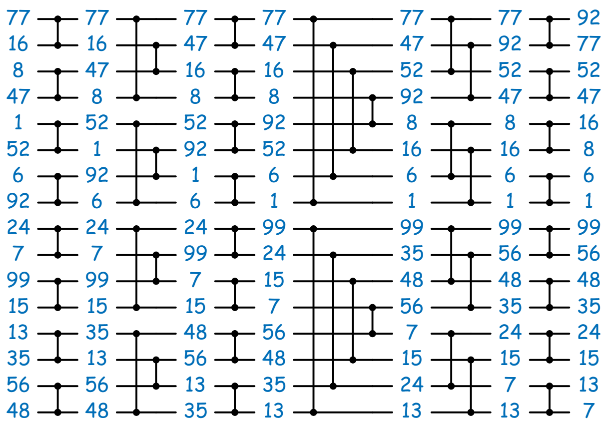
Odd-Even Sort Example



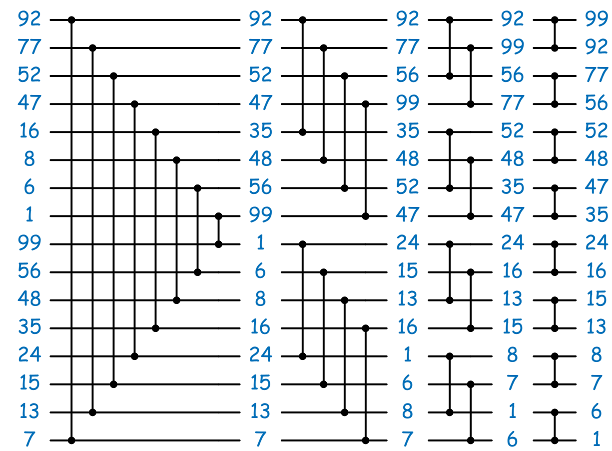
Example: Bitonic Sorter



Bitonic Sort Example (I)



Bitonic Sort Example (II)



Mapping and Reducing in Parallel

- The `map` function in Python conceptually provides many opportunities for parallel computation, if the computations of invidividual items is *independent*.
- Less obviously, so does `reduce`, if the operation is *associative*. If list `L == L1 + L2`, and `op` is an associative operation, then

  `reduce(op, L) == op(reduce(op, L1), reduce(op, L2))`

  and the two smaller reductions can happen in parallel.

Map-Reduce

- Google[tm] patented an embodiment of this approach (the validity of which is under dispute). Here's a very simplified version.
- User specifies a mapping operation and a reduction operation.
- In the mapping phase, the map operation is applied to each item of data, yielding a *list of key-value pairs* for each item.
- The reduce operation is then applied on all the values for each distinct key.
- The final result is a list of key-value pairs, with each value being the reduction of the values for that key as produced by the mapping phase.
- Standard simple example:
  - Each input item is a page of text.
  - The map operation takes a page of text ("The cow jumped over the moon...") and produces a list with the words as keys and the value 1 (`("the", 1), ("cow", 1), ("jumped", 1), ...`).
  - The reduce phase now sums the values for each key.
  - Result: for each key (word), get the total count.

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

x = 6

- 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

Coordinating Parallel Computation

Let's go back to bank accounts:

```
class BankAccount:
    def __init__(self, initial_balance):
        self._balance = initial_balance
    @property
    def balance(self): return self._balance
    def withdraw(amount):
        if amount > self._balance:
            raise ValueError("insufficient funds")
        else:
            self._balance -= amount
            return self._balance
```

acct = BankAccount(10)	
acct.withdraw(8)	acct.withdraw(7)

- At this point, we'd *like* to have the system raise an exception for one of the two withdrawals, and to set `acct.balance` to either 2 or 3, depending on with withdrawer gets to the bank first, like this...

Desired Outcome

```
class BankAccount:
    def withdraw(amount):
        if amount > self._balance:
            raise ValueError("insufficient funds")
        else:
            self._balance -= amount
            return self._balance
```

acct = BankAccount(10)	
acct.withdraw(8)	acct.withdraw(7)

```
READ acct._balance ->  10
WRITE acct._balance -> 2
                                    READ acct._balance -> 2
                                    <raise exception>
```

But instead, we might get...

Undesireable Outcome

```
class BankAccount:
    def withdraw(amount):
        if amount > self._balance:
            raise ValueError("insufficient funds")
        else:
            self._balance -= amount
            return self._balance
```

acct = BankAccount(10)	
acct.withdraw(8)	acct.withdraw(7)

```
READ acct._balance ->  10        READ acct._balance -> 10
WRITE acct._balance -> 2
                                 WRITE acct._balance -> 3
```

Oops!

Serializability

- We define the desired outcomes as those that would happen if withdrawals happened sequentially, in *some* order.
- The *nondeterminism* as to which order we get is acceptable, but results that are inconsistent with both orderings are not.
- These latter happen when operations overlap, so that the two processes see *inconsistent* views of the account.
- We want the withdrawal operation to act as if it is *atomic*—as if, once started, the operation proceeds without interruption and without any overlapping effects from other operations.