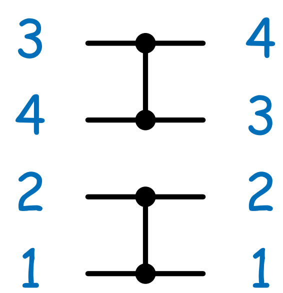
Lecture 33: Concurrency

- 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

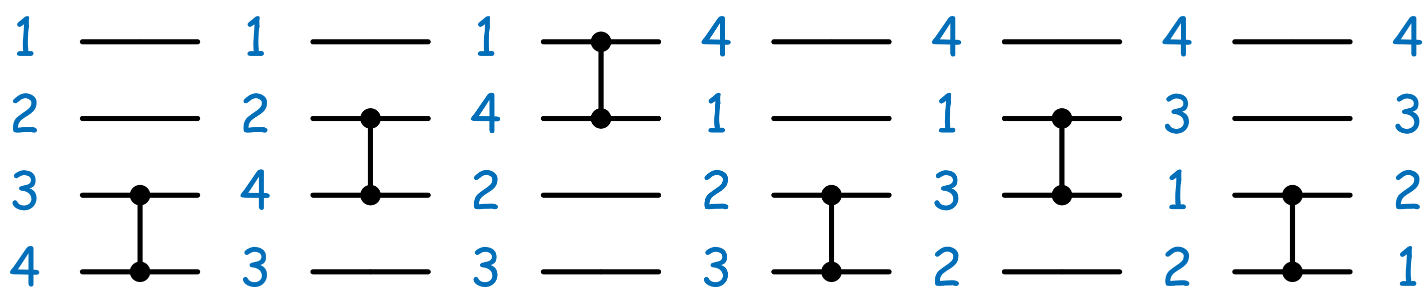
- Sorting a list presents obvious opportunities for parallelization.
- Can illustrate various methods diagrammatically using *comparators* as an elementary unit:



- 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.

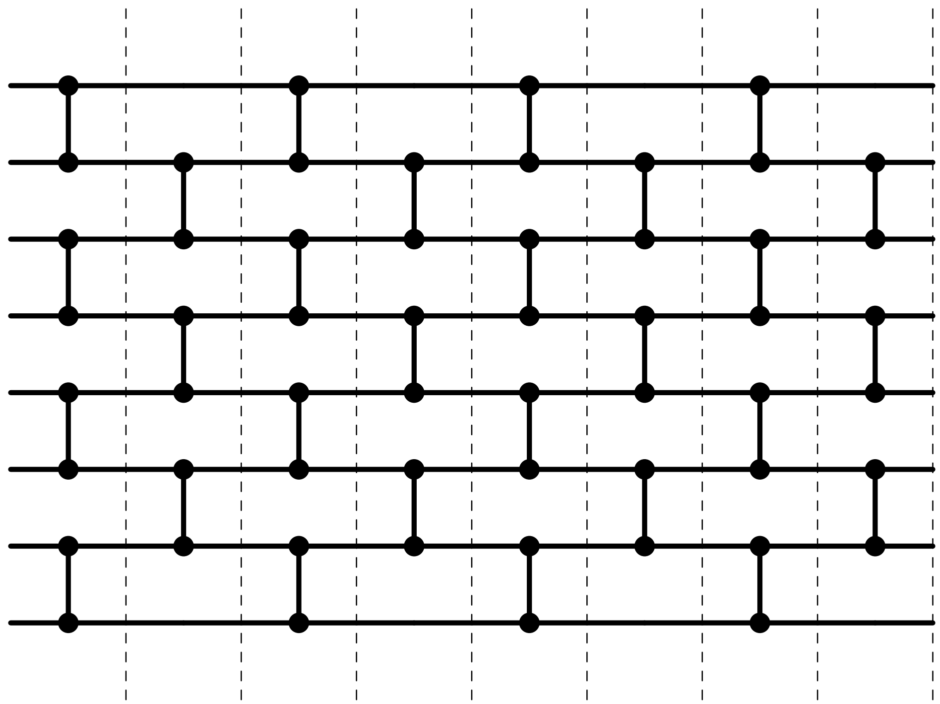
Sequential sorting

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

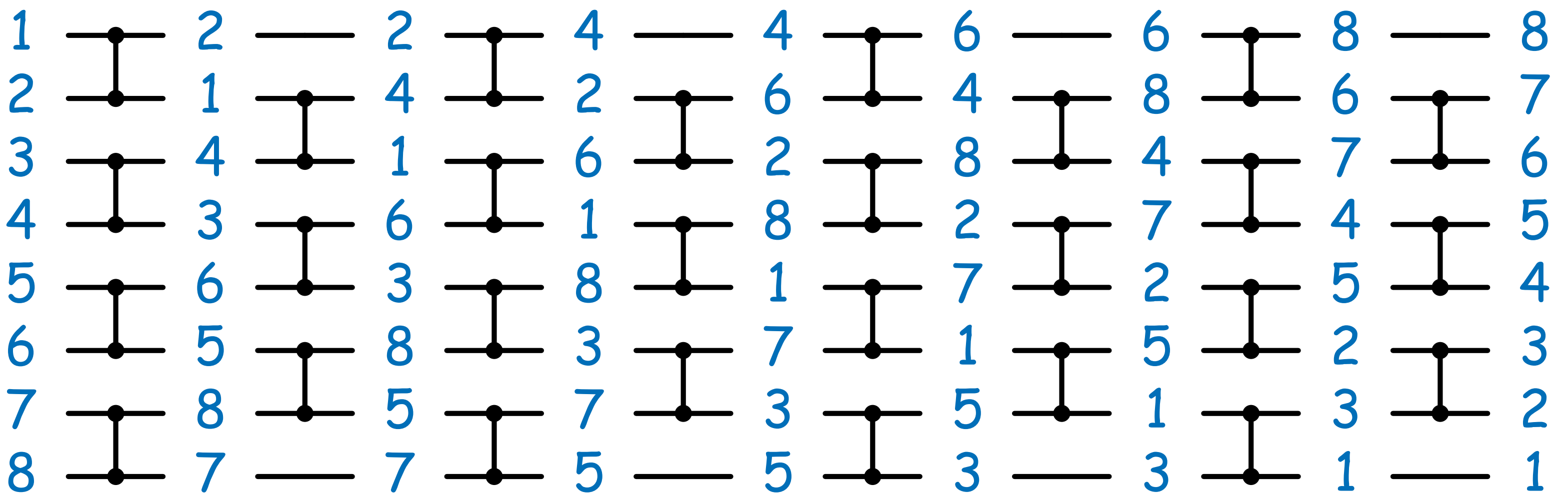


- Each comparator is a separate operation in time.
- In general, there will be $\Theta(N^2)$ steps.
- But since some comparators operate on distinct data, we ought to be able to overlap operations.

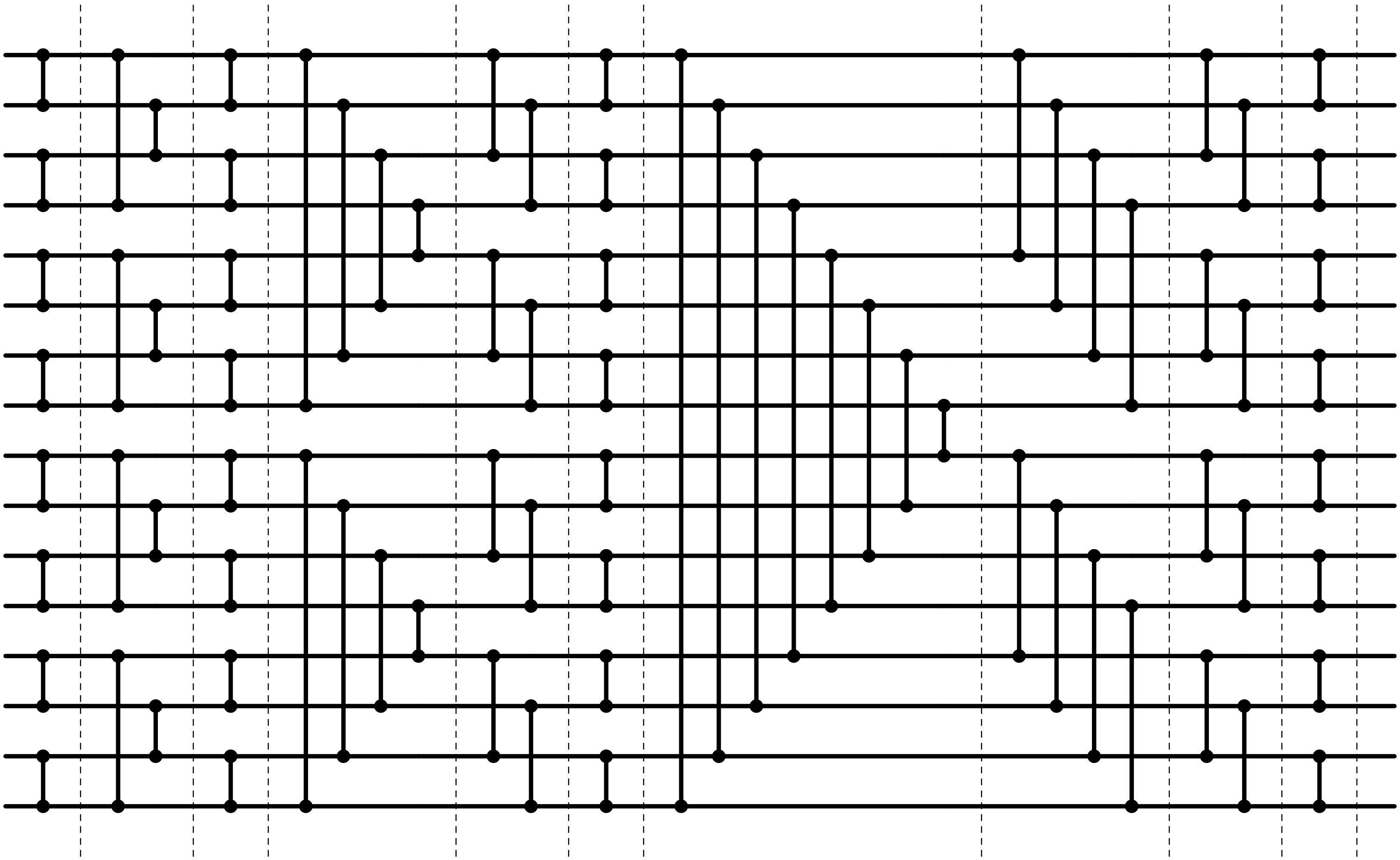
Odd-Even Transposition Sorter



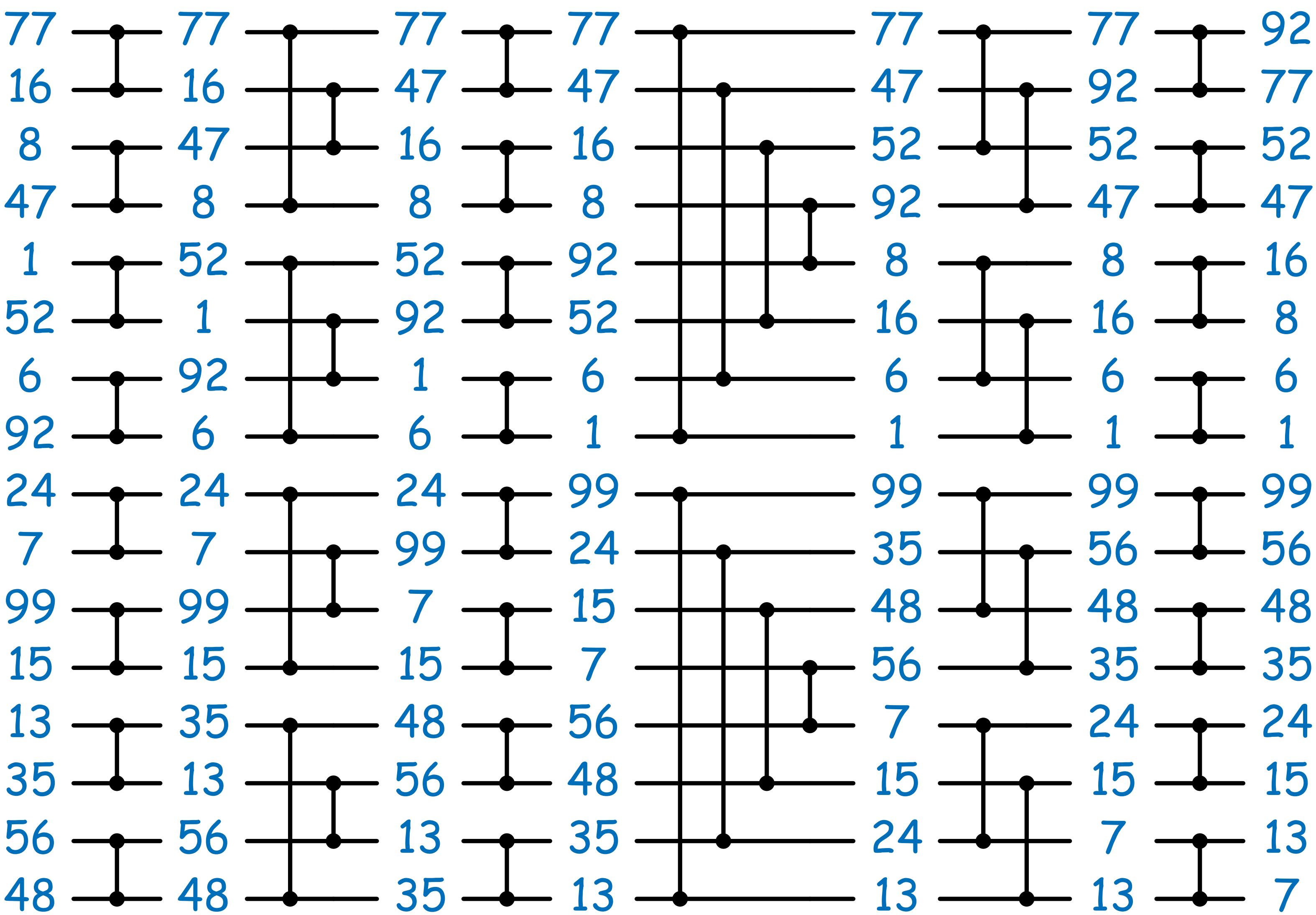
Odd-Even Sort Example



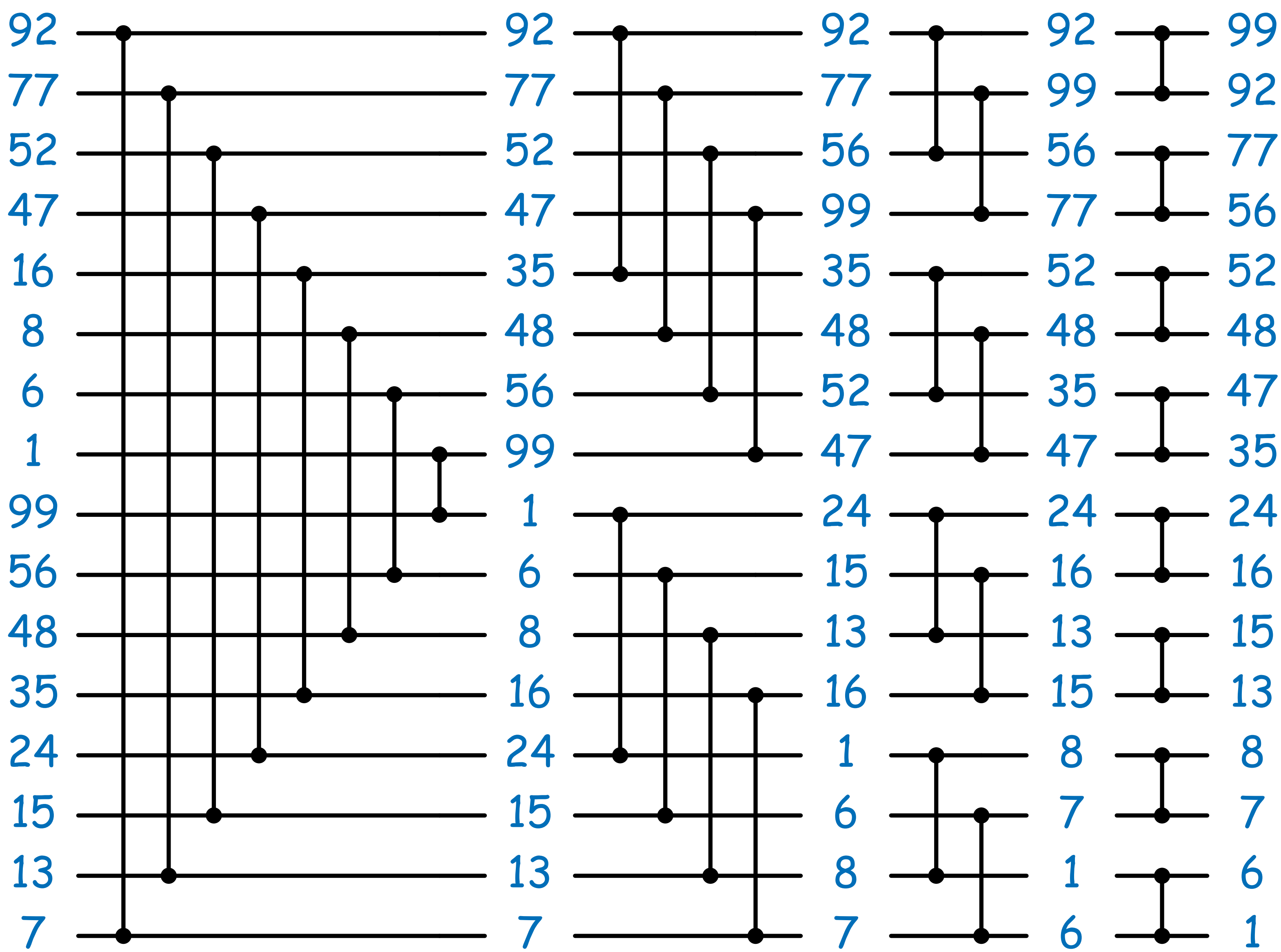
Example: Bitonic Sorter



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.

<table>
<tr><td colspan="2" align="center">x = 5</td></tr>
<tr><td>x = square(x)</td><td>y = x + 1</td></tr>
<tr><td>P1</td><td>P2</td></tr>
<tr><td>READ x -> 5
(calculate 5*5 -> 25)
WRITE 25 -> x
|</td><td>|
READ x -> 5
(calculate 5+1 -> 6)
WRITE 6 -> y</td></tr>
<tr><td colspan="2" align="center">x = 25
y = 6</td></tr>
</table>

- 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 = 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`?

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 = 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

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.

One Solution: Critical Sections

- Some programming languages (e.g., Java) have special syntax for this. In Python, we can arrange something like this:

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

- The `with` construct:
  1. Calls the `__enter__()` method of its "context manager" argument (here, some object we'll call `CriticalSectionManager`);
  2. Executes the body (indented portion);
  3. Finally, it calls the `__exit__()` method on the context manager. It guarantees that it will *always* do so, no matter how you exit from the body (via `return`, exception, etc.).
- The idea is that our *CriticalSectionManager* object should let just one process through at a time. How?

Locks

- To implement our critical sections, we'll need some help from the operating system or underlying hardware.
- A common low-level construct is the *lock* or *mutex* (for "mutual exclusion"): an object that at any given time is "owned" by one process.
- If `L` is a lock, then
  - `L.acquire()` attempts to own `L` on behalf of the calling process. If someone else owns it, the caller *waits* for it to be release.
  - `L.release()` relinquishes ownership of `L` (if the calling process owns it).

Implementing Critical Regions

- Using locks, it's easy to create the desired context manager:

```
from threading import Lock

class CriticalSection:
    def __init__(self):
        self.__lock = Lock()

    def __enter__(self):
        self.__lock.acquire()

    def __exit__(self, exception_type, exception_val, traceback):
        self.__lock.release()
CriticalSectionManager = CriticalSection()
```

- The extra arguments to `__exit__` provide information about the exception, if any, that caused the **with** body to be exited.
- (In fact, the bare `Lock` type itself already has `__enter__` and `__exit__` procedures, so you don't really have to define an extra type).

Granularity

- We've envisioned critical sections as being atomic with respect to *all* other critical sections.
- Has the advantage of simplicity and safety, but causes unnecessary waits.
- In fact, different accounts need not coordinate with each other. We can have a separate critical section manager (or lock) for each account object:

```
class BankAccount:
    def __init__(self, initial_balance):
        self._balance = initial_balance
        self._critical = CriticalSection()
    def withdraw(self, amount):
        with self._critical:
          ...
```

- That is, can produce a solution with finer *granularity* of locks.

Synchronization

- Another kind of problem arises when different processes must communicate. In that case, one may have to wait for the other to send something.
- This, for example, doesn't work too well:

```
class Mailbox:
    def __init__(self):
        self._queue = []
    def deposit(self, msg):
        self._queue.append(msg)
    def pickup(self):
        while not self._queue:
            pass
        return self._queue.pop()
```

- Idea is that one process deposits a message for another to pick up later.
- What goes wrong?

Problems with the Naive Mailbox

```
class Mailbox:
    def __init__(self):
        self._queue = []
    def deposit(self, msg):
        self._queue.append(msg)
    def pickup(self):
        while not self._queue:
            pass
        return self._queue.pop()
```

- *Inconsistency:* Two processes picking up mail can find the queue occupied simultaneously, but only one will succeed in picking up mail, and the other will get exception.
- *Busy-waiting:* The loop that waits for a message uses up processor time.
- *Deadlock:* If one is running two logical processes on one processor, busy-waiting can lead to nobody making any progress.
- *Starvation:* Even without busy-waiting one process can be shut out from ever getting mail.

Conditions

- One way to deal with this is to augment locks with *conditions:*

```
from threading import Condition
class Mailbox:
    def __init__(self):
        self._queue = []
        self._condition = Condition()
    def deposit(self, msg):
        with self._condition:
            self._queue.append(msg)
            self._condition.notify()
    def pickup(self):
        with self._condition:
            while not self._queue:
                self._condition.wait()
            return self._queue.pop()
```

- Conditions act like locks with methods `wait`, `notify` (and others).
- `wait` releases the lock, waits for someone to call `notify`, and then reacquires the lock.

Another Approach: Messages

- Turn the problem inside out: instead of client processes deciding how to coordinate their operations on data, let the *data* coordinate its actions.
- From the Mailbox's perspective, things look like this:

```
self._queue = []
while True:
   wait for a request, R, to deposit or pickup
   if R is a deposit of msg:
      self.__queue.append(msg)
      send back acknowledgement
   elif self.__queue and R is a pickup:
      msg = self.__queue.pop()
      send back msg
```

Rendezvous

- Following ideas from C.A.R Hoare, the Ada language used the notion of a *rendezvous* for this purpose:

```
task type Mailbox is
   entry deposit(Msg: String);
   entry pickup(Msg: out String);
end Mailbox;

task body Mailbox is
    Queue: ...
begin
    loop
        select
          accept deposit(Msg: String) do Queue.append(Msg); end;
        or when not Queue.empty =>
          accept pickup(Msg: out String) do Queue.pop(Msg); end;
        end select;
    end loop;
end;
```