Department of Computer Science
University of Bristol

COMS20001 - Concurrent Computing

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Lecture 05

Replication & Pipelining

Sion Hannuna | sh1670@bristol.ac.uk
Dan Page | daniel.page@bristol.ac.uk

Process Replication using Replicated **PAR**

- builds an array of **structurally similar** parallel processes
- parameterise processes using the replicator index (e.g. **i**)
- **Example**: use together with channels and arrays for process chains, buffers, queues etc.

replication.xc

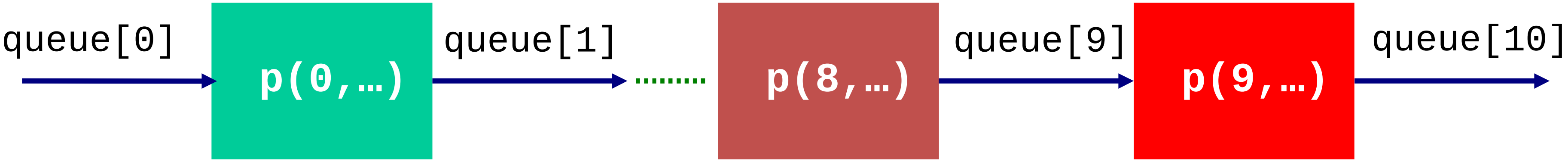
```
// chain of processes
...
void chainElement( chanend cInput, chanend cOutput) { ... }

int main ( void ) {
  chan c[4];
   par (int i=0; i<4; i++)
     chainElement(c[i], c[(i+1)%4]);
  return 0;
}
```

Replicated **PAR** is key to elegant concurrent programming!

Example: Process Buffer via Replicated **PAR**

```
...
  chan queue[11];                        // array of 11 channels
  par (int i=0; i<10; i++) {  // 10 parallel processes p in buffer
    int a;
    queue[i] :> a;
    p(i,a);
    queue[i+1] <: a;
  }
...
```

Is this legal (it's not)?



NOTE!
Still need processes to feed the queue and to bleed the queue

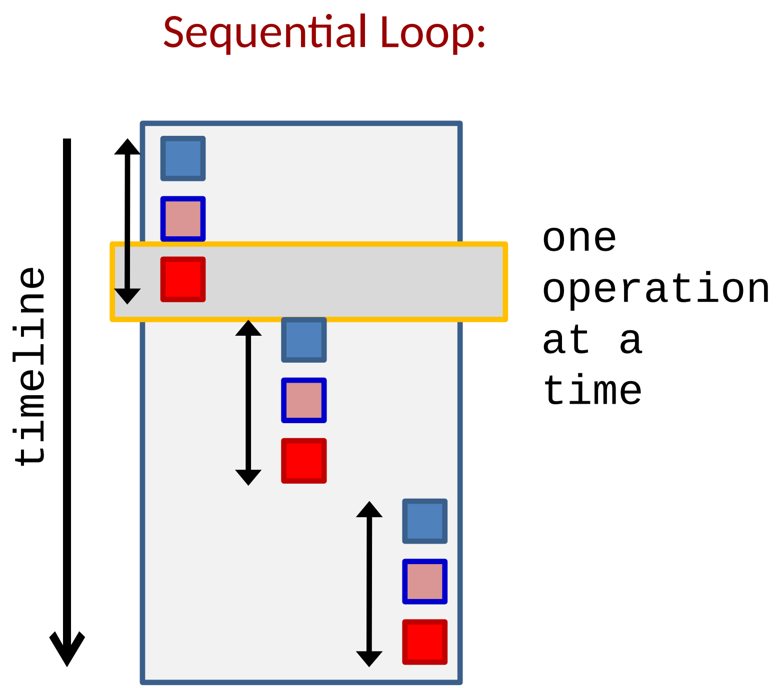
buffer.xc

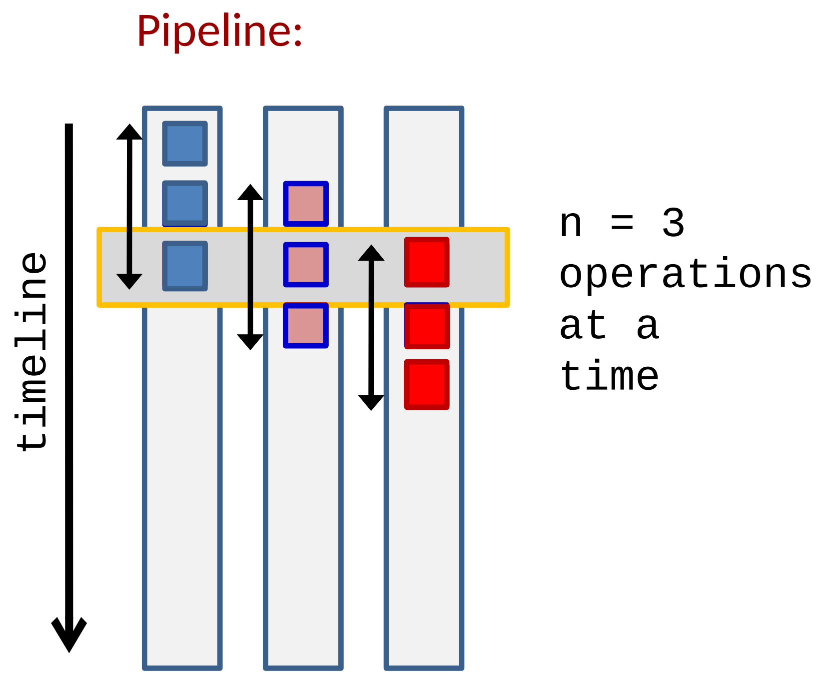
Example: Buffer via Replication and Nesting with **PAR**

```
...
  void inputProcess(chanend c){ //FEEDING buffer pipeline
    while (1)
      c <: 1; //send input data item, e.g. key from keyboard, sensor data etc...
  }
...
  void outputProcess(chanend c){ //DRAINING buffer pipeline
    int x;
    while (1) {
      c :> x;          //drain element from last buffer element
      printf("%d",x);  //display on screen
    }
  }
...
  void bufferProcess(chanend cIn, chanend cOut){ //BUFFER one element
    int x;
    while (1) {
      cIn :> x;   //try to read (and hold, i.e. buffer)
      cOut <: x;  //try send data item on to next buffer
    }
  }
...
  int main(void) {  //SETUP CONCURRENT PROGRAM
    chan queue[14]; //create 14 channels
    par {         //align 15 concurrently running processes in pipeline
      on tile[0]: inputProcess(queue[0]);    //start first process of pipeline
      on tile[1]: outputProcess(queue[13]);  //start last process of pipeline
      par (int i=0;i<13;i++) {         //replicate 13 buffer processes
        on tile[i%2]: bufferProcess(queue[i],queue[i+1]);
      }
    }
    return 0;
  }
   ...
```

Pipeline Processing

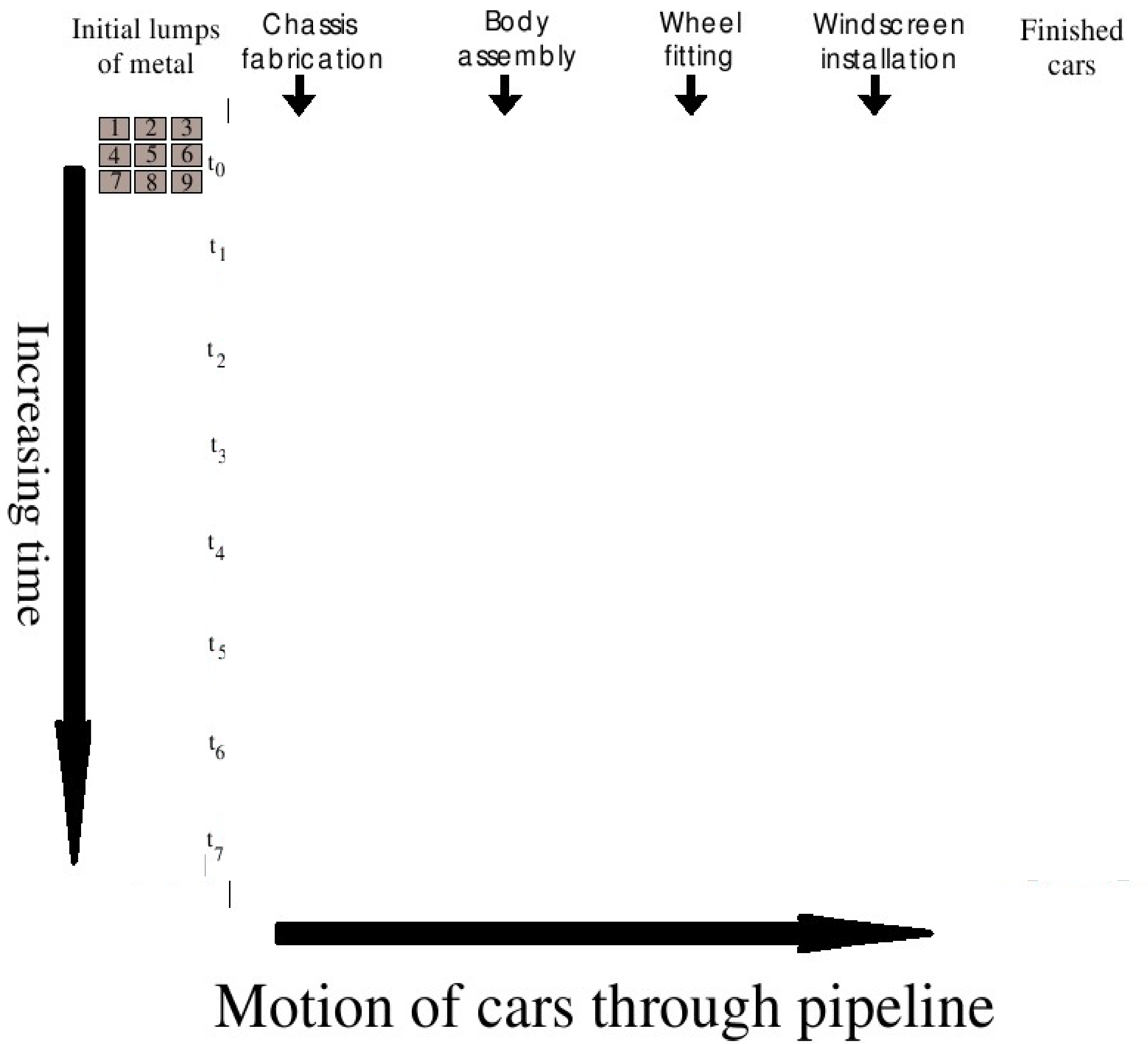
- Pipeline stages transform the data before passing it on in a chain. Can be (much) faster than using a loop.
- Speed advantage of pipeline is due to overlapping in time





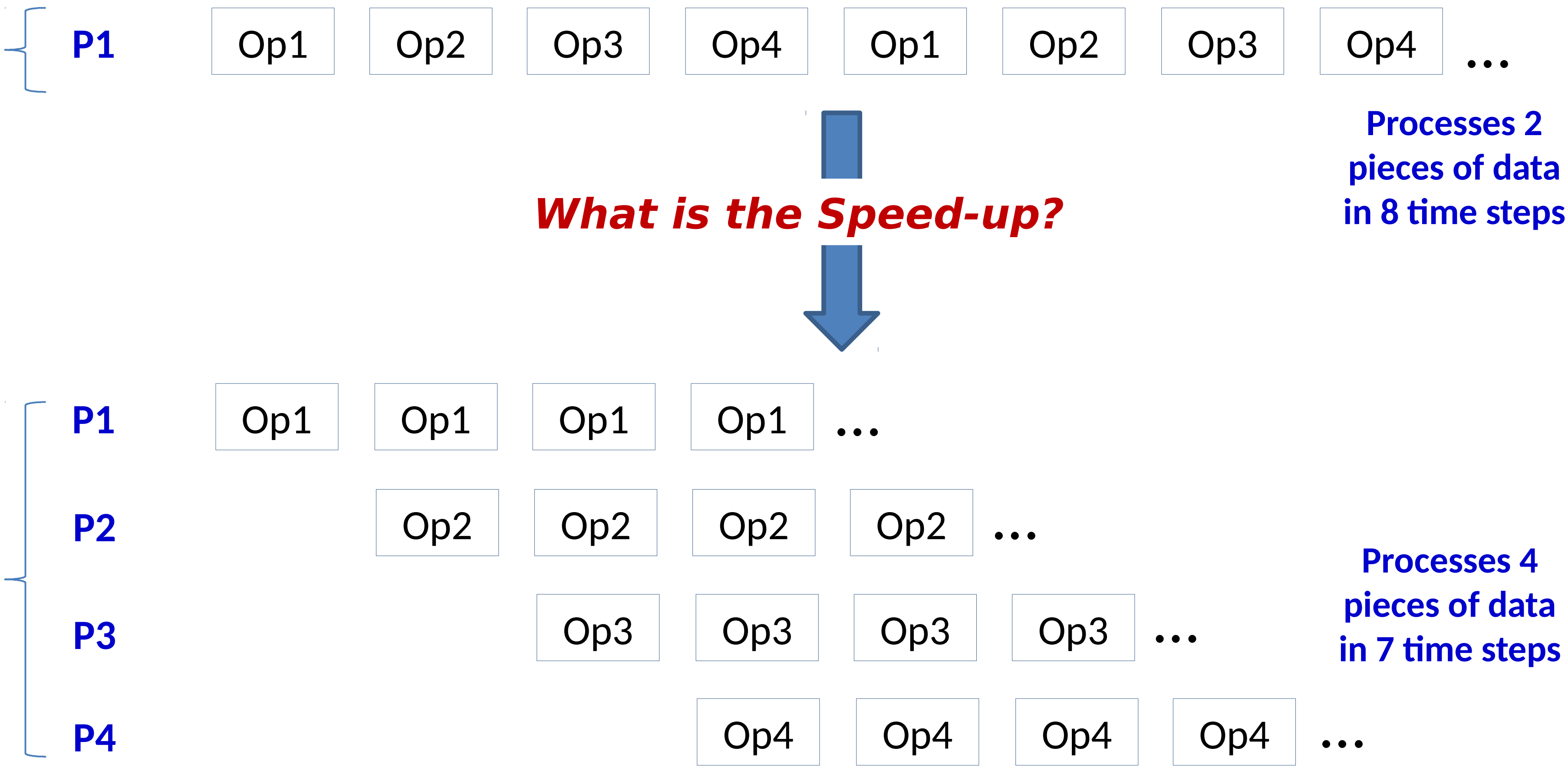
Max time-saving achieved if each stage runs on its own processor.

Pipelines: Car making analogy



From "Alan Chalmers, Practical Parallel Processing, 1996"

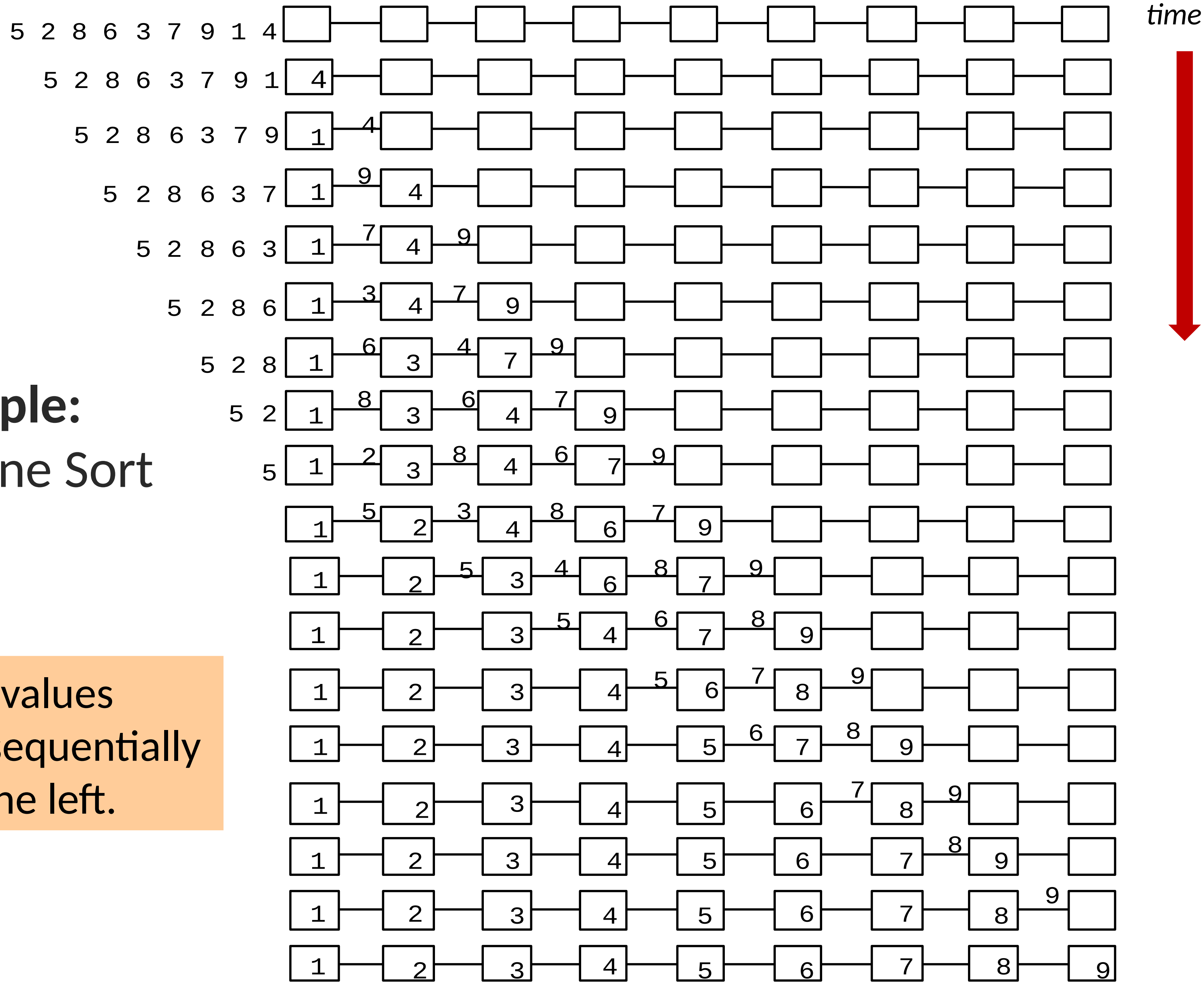
Pipeline Processing: speed-up?



We needed 4 processors to get only 2x speed-up.

More on this later…

Example:
Pipeline Sort



...with values input sequentially from the left.

Example: Pipeline Sort

Sort a stream of **`N`** numbers with a pipeline of **`N`** processes!

- Each process has two local variables: **`lowest`** and **`next`**.

- Each number enters a process and is compared to value in **`lowest`**.
  - If not smaller than **`lowest`** then pass to next pipeline stage
  - If smaller than **`lowest`** then keep it and pass on previous lowest

- When all numbers are processed, pass final value of **`lowest`** on

Develop code using Replicated **PAR**!

XC Pipeline Sort Code I

- To sort a sequence of 10 numbers:

```
// XC code to compare numbers for each pipeline stage
...
  int next;
  cIn :> next;
  if (next >= lowest) {
      cOut <: next;
    }
  else {
    cOut <: lowest;
    lowest = next;
  }
...
```

XC Pipeline Sort Code II

- Now repeat comparison code 9 times in each pipeline stage:

```
// XC code for one single pipeline sort stage

void sortStage(chanend cIn, chanend cOut) {
  int lowest;
  cIn :> lowest;
  for (int j=0;j<9;j++) {
    int next;
    cIn :> next;
    if (next >= lowest) {
      cOut <: next;
    }
    else {
      cOut <: lowest;
      lowest = next;
    }
  }
  cOut <: lowest;
}
```

XC Pipeline Sort Code III

```
// XC code fragment for pipeline sort chain
...
void sortStage(chanend cIn, chanend cOut) {
  int lowest;
  cIn :> lowest;
  for (int j=0;j<9;j++) {
    int next;
    cIn :> next;
    if (next >= lowest) {
      cOut <: next;
    }
    else {
      cOut <: lowest;
      lowest = next;
    }
  }
  cOut <: lowest;
}
...
int main(void) {
  chan pipe[11]; ...
  par (int i=0; i<10; i++) {
    on tile[i%2]: sortStage(pipe[i],pipe[i+1]);
  }
  return 0;
}
```

- Now replicate 10 times to get 10 parallel processes, one for each pipeline stage
- Note, we need one channel more than the number of processes:

  chan pipe[11];

Main program

XC Pipeline Sort Code IV

- Processes to feed and bleed the pipeline

```
// XC code to feed and bleed pipeline
...
void inputProcess(chanend c) {
  for (int j=0;j<10;j++)
    c <: readUnsortedNumber(j);
}
...
void outputProcess(chanend c) {
  for (int j=0;j<10;j++) {
    int x;
    c :> x;
    printf("%d,",x);
  }
}
...
```

pipelinesort.xc

Full XC Pipeline Sort Code

```
void inputProcess(chanend c) {  //FEEDING pipeline
  for (int j=0;j<10;j++)
    c <: readUnsortedNumber(j);
}
...
void outputProcess(chanend c) { //BLEEDING pipeline
  for (int j=0;j<10;j++) {
    int x;
    c :> x;
    printf("%d,",x);
} }
...
void sortStage(chanend cIn, chanend cOut) { //one STAGE of pipeline
  int lowest;
  cIn :> lowest;
  for (int j=0;j<9;j++) {
    int next;
    cIn :> next;
    if (next >= lowest) {
      cOut <: next;
    }
    else {
      cOut <: lowest;
      lowest = next;
  } }
  cOut <: lowest;
}
...
int main(void) {//SETUP CONCURRENT PROGRAM
  chan pipe[11]; ...
  par {
    inputProcess(pipe[0]);
    outputProcess(pipe[10]);
    par (int i=0; i<10; i++) {
      on tile[i%2]: sortStage(pipe[i],pipe[i+1]);
    }
  }
  return 0;
}
```

More Efficient XC Pipeline Sort Code

pipelinesort2.xc

```
...

void sortStage(int i, chanend cIn, chanend cOut) {
  int lowest;
  cIn :> lowest;
  for (int j=0;j<9-i;j++) { //sort unsorted part
    int next;
    cIn :> next;
    if (next >= lowest) {
      cOut <: next;
    }
    else {
      cOut <: lowest;
      lowest = next;
    }
  }
  cOut <: lowest;
  for (int j=0;j<i;j++) { //copy already sorted part
    cIn :> lowest;
    cOut <: lowest;
} }
...
int main(void) {
  chan pipe[11];...
  par (int i=0; i<10; i++) {
    on tile[i%2]: sortStage(i,pipe[i],pipe[i+1]);
  }
  return 0;
}
```

TAKE HOME EXERCISE

- Data already sorted by previous pipeline nodes
- **do not sort in these cases, but simply copy data**

Parallelism suitable for Pipelining

In general, a program that would otherwise be written using two or more nested **`WHILE`** loops can often be transformed into a pipelined program.

```
WHILE  test1
  WHILE  test2
         ...
```

No speed advantage unless the inner loop produces a value to pass on early in its execution.

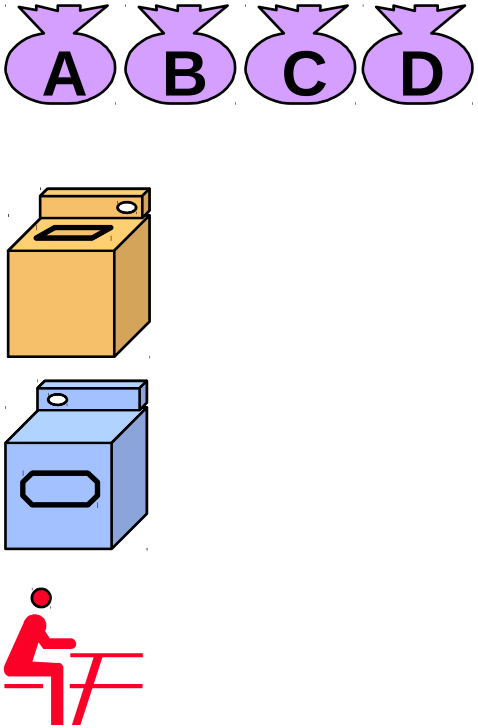
if value is only produced at termination, then there is no overlap, hence no parallelism then to be exploited in a pipeline.

Simple Puzzle: Traditional Pipeline Concept

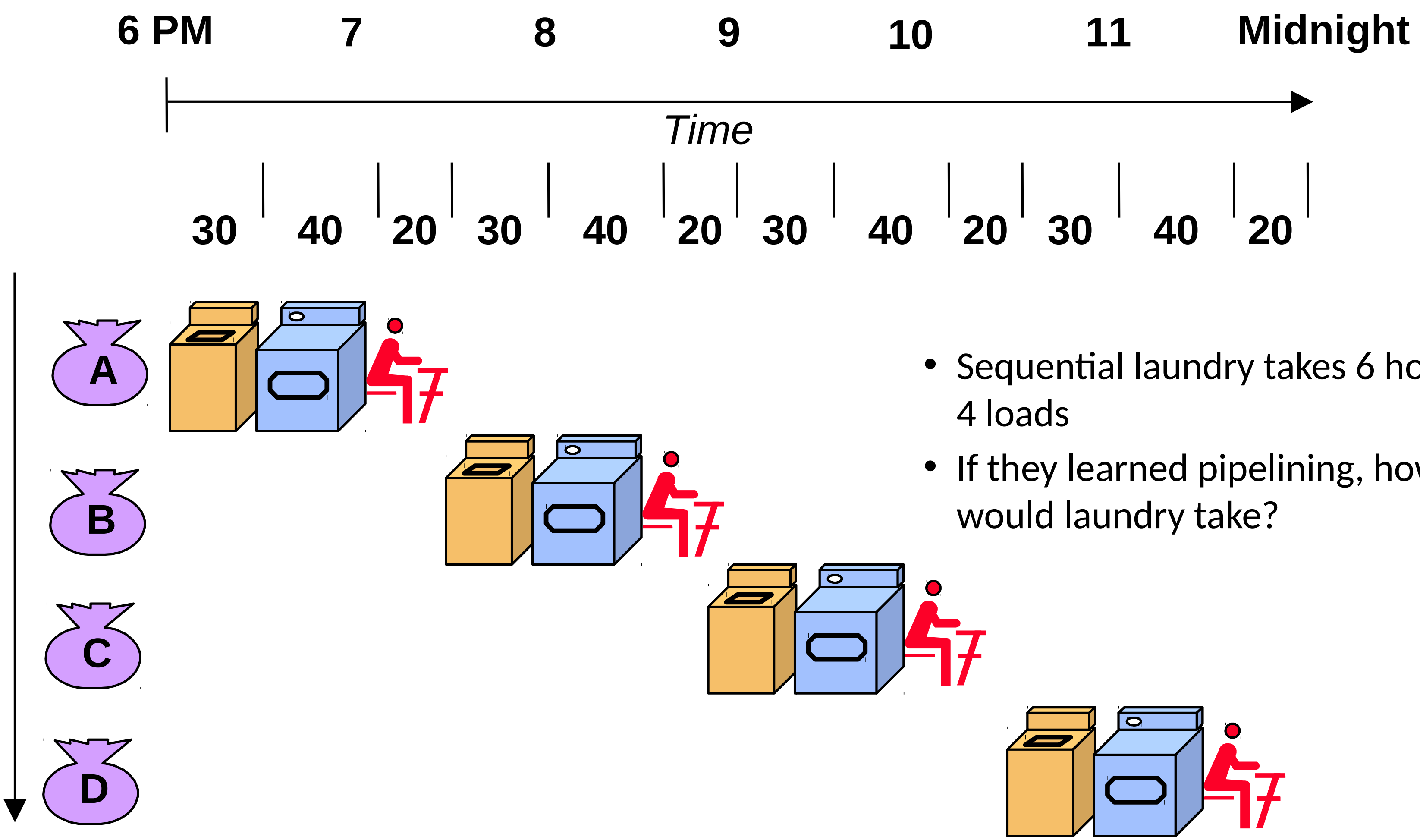
Dirty Laundry

Ann, Brian, Cathy, Dave
each have one load of clothes
to wash, dry, and fold

- Washer takes 30 minutes
- Dryer takes 40 minutes
- “Folder” takes 20 minutes

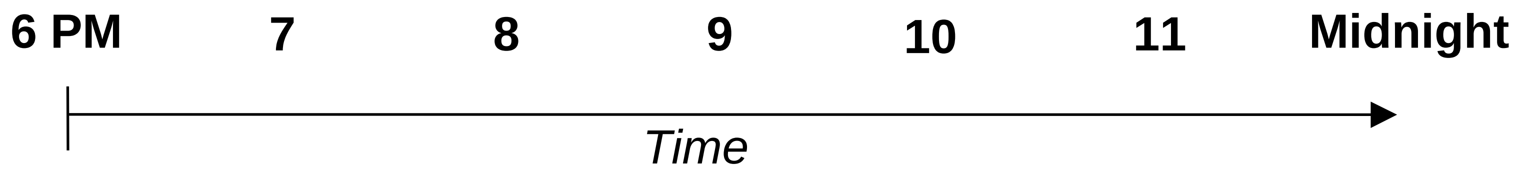


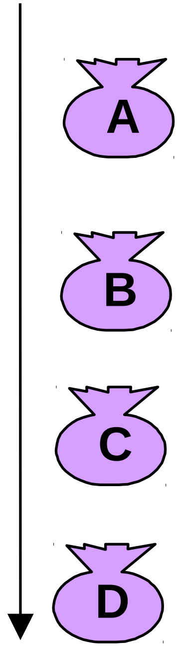
Sequential Approach



- Sequential laundry takes 6 hours for 4 loads
- If they learned pipelining, how long would laundry take?

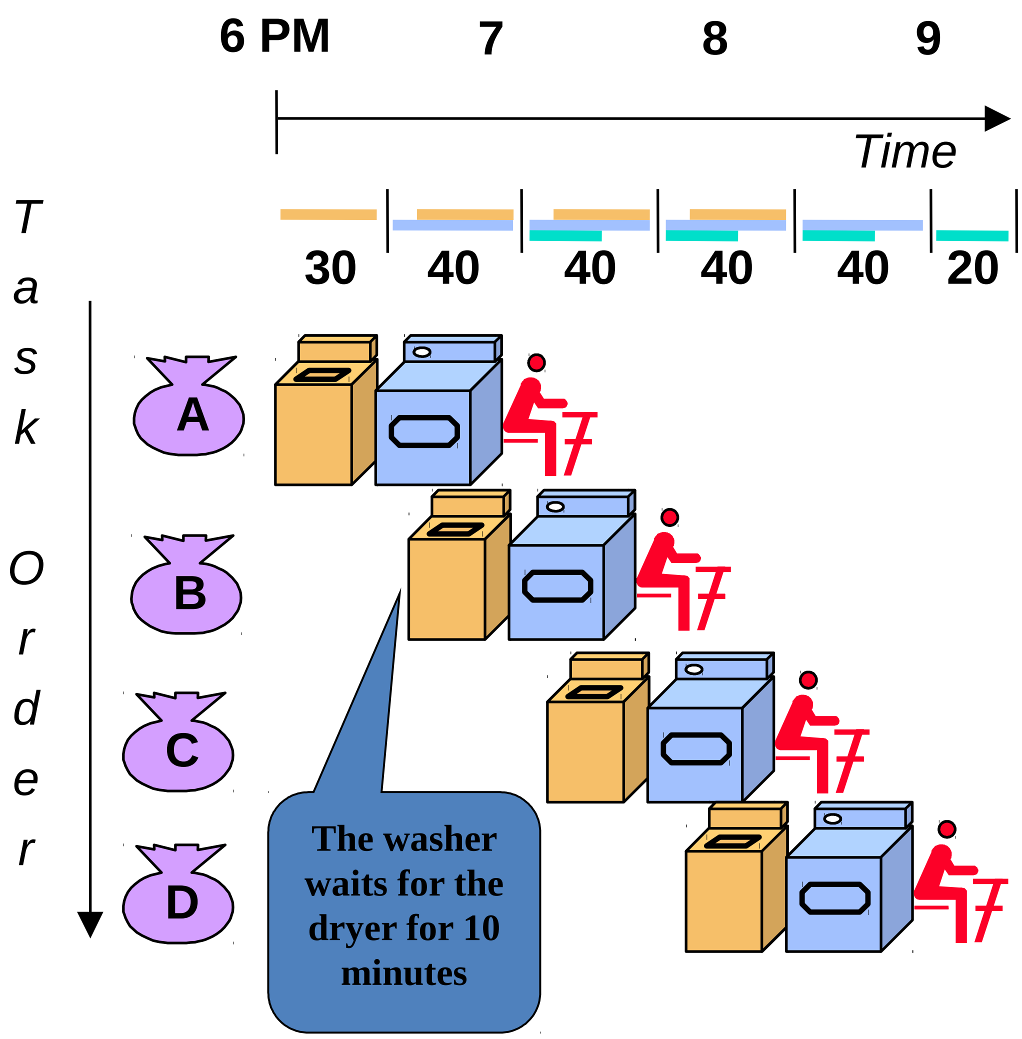
Simple Pipeline Approach





If they learned pipelining, how long would laundry take and so what time would they finish?

Simple Pipeline Approach



- Pipelining doesn't help latency of single task, it helps throughput of entire workload
- Pipeline rate limited by slowest pipeline stage
- Unbalanced lengths of pipeline stages reduce speedup
- Potential speedup = Number of pipeline stages
- Time to feed and bleed pipeline reduces speedup

Pipelined laundry takes 3.5 hours for 4 loads

Livelock

A form of deadlock:
when two or more processes continue to execute, but make no progress towards the ultimate goal.

Examples:

- When there is an endless loop in program execution: e.g. it occurs when a process repeats itself, because it continues to receive erroneous information.
- When a process that calls another process is itself called by that process, and there is no logic to detect this situation and stop the operation.

So a livelock differs from a "deadlock," in that processing continues to take place, rather than just waiting in an idle loop.

Livelock: Basic XC examples


```
while (x) {
  ch1 :> x
  ... Do something
  ch2 <: y
}
```

```
while (x) (
  ... Do something
  ch1 <: x
  ch2 :> y
}
```

Two processes that will infinitely just communicate amongst themselves while X never becomes 0.

Basic Disjointness Rules [for Variables]

The rules for disjointness on a set of threads $T_0 \ldots T_i$ and *a* set of variables $V_0 \ldots V_j$:

- ❖ If thread T_x contains any modification to variable V_m then none of the other threads (T_t; $t \neq x$) are allowed to use V_m
- ❖ If thread T_x contains a reference to variable V_m then none of the other threads (T_t ; $t \neq x$) are allowed to modify V_m
- ❖ If thread T_x contains a reference to port V_p then none of the other threads are allowed to use V_p

- a group of threads can have **shared read-only access** to a local variable, but only a single thread can have **exclusive read-write access.**

- disjointness rules for variables guarantee that each thread has a well-defined meaning that is independent of the order in which instructions in other threads are scheduled

Examples

```
main (void) {
  int i=1,j=2,k=3;
  par {
    i = k + 1;        // Thread X
    j = k - 1;        // Thread Y
  }
}
```

Legal or not?

```
main (void) {
  int i=1,j=2,k;
  par {
    i = j + 1;        // Thread X
    k = i - 1;        // Thread Y
  }
}
```

Legal or not?

```
main (void) {
  int a[2];
  par {
    a[0] = f(0);       // Thread X
    a[1] = f(1);       // Thread Y
  }
}
```

Legal or not?