Parallel Sequences

COS 326

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Princeton University

Credits:

Dan Grossman, UW

http://homes.cs.washington.edu/~djg/teachingMaterials/spac

Blelloch, Harper, Licata (CMU, Wesleyan)

Last Time: Parallel Programming Disciplines

Programming with shared mutable data is very hard!

With pure functional code and parallel futures, many error modes disappear

Are there more great abstractions like futures?

- you betcha!

What if you had a really big job to do?

Example: Create an index of every web page on the planet.

- Google does that regularly!
- There are billions of them!

Example: Search facebook for a friend or twitter for a tweet

To get big jobs done, we typically need 1000s of computers, but:

- how do we distribute work across all those computers?
- you definitely can't use shared-memory parallelism because the computers don't share memory!
- when you use 1 computer, you just hope it doesn't fail. If it does, you go to the store, buy a new one and restart the job.
- when you use 1000s of computers at a time, failures become the norm. what to do when 1 of 1000 computers fail? Start over?

Big Jobs ---> Better Abstractions

Need high-level interfaces to shield application programmers from the complex details. Complex implementations solve the problems of distribution, fault tolerance and performance.

Common abstraction: Parallel collections

Example collections: sets, tables, dictionaries, sequences

Example bulk operations: create, map, reduce, join, filter

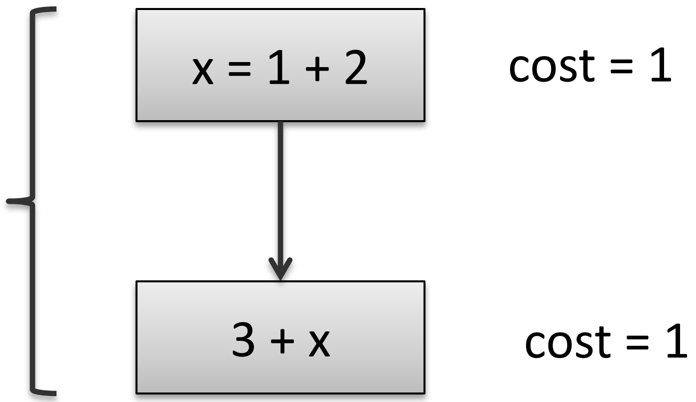
COMPLEXITY OF PARALLEL ALGORITHMS

Visualizing Computational Costs

```
let x = 1 + 2 in
3 + x
```

Visualizing Computational Costs

let x = 1 + 2 in
3 + x



Visualizing Computational Costs

let x = 1 + 2 in
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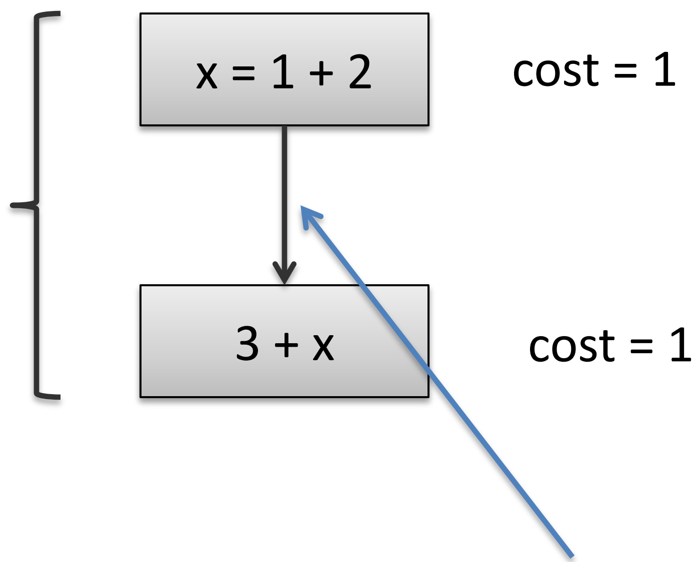
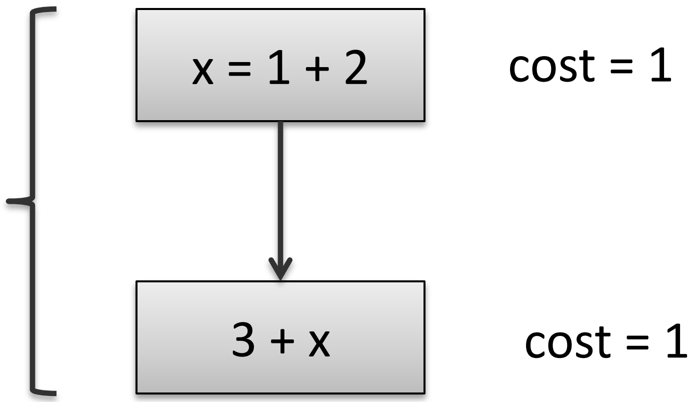


dependence:
x = 1 + 2 *happens before* 3 + x

Visualizing Computational Costs

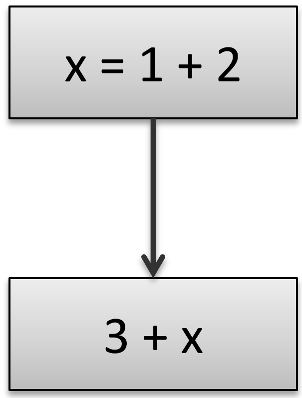
let x = 1 + 2 in
3 + x



<u>**Execution of dependency diagrams:**</u> A processor can only begin executing the computation associated with a block when the computations of all of its predecessor blocks have been completed.

Visualizing Computational Costs

step 1:
execute first block



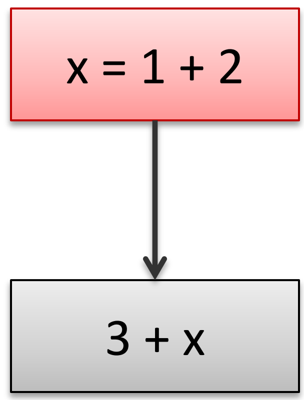
cost = 1

cost = 1

Cost so far: 0

Visualizing Computational Costs

step 1:
execute first block

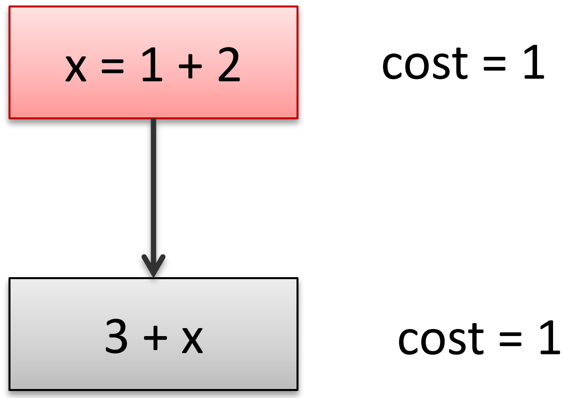


cost = 1

cost = 1

Cost so far: 1

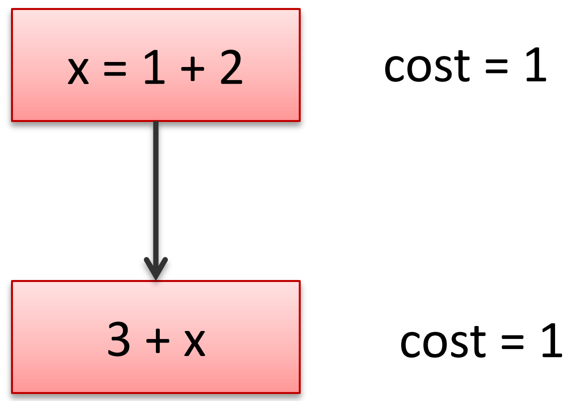
Visualizing Computational Costs



step 2:
execute second block because all of its predecessors have been completed

Cost so far: 1

Visualizing Computational Costs

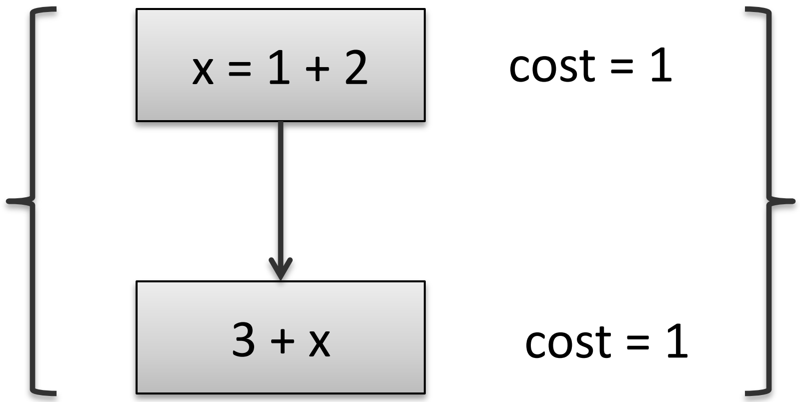


step 2:
execute second block
because all of its
predecessors have
been completed

Cost so far: 1 + 1

Visualizing Computational Costs

let x = 1 + 2 in
3 + x



total cost
= 1 + 1
= 2

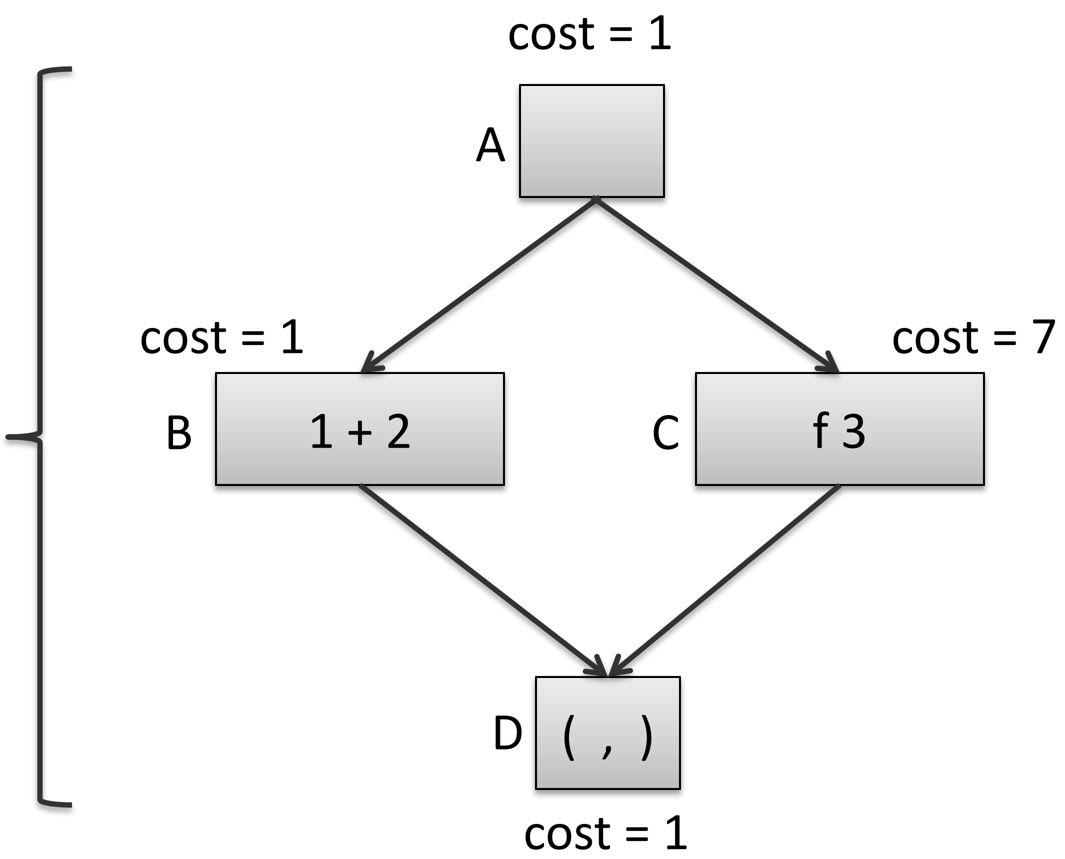
Visualizing Computational Costs

(1 + 2 || f 3)

parallel pair:
compute both left and right-hand sides independently
return pair of values
(easy to implement using futures)

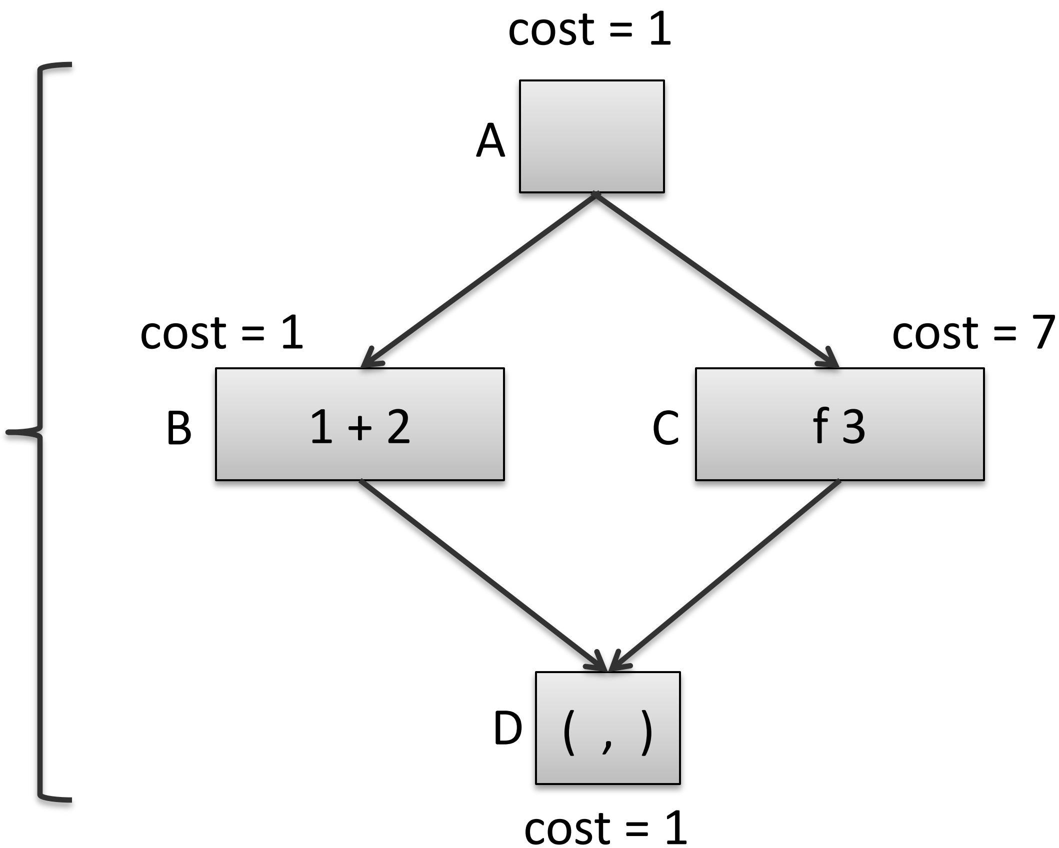
Visualizing Computational Costs

(1 + 2 || f 3)



Visualizing Computational Costs

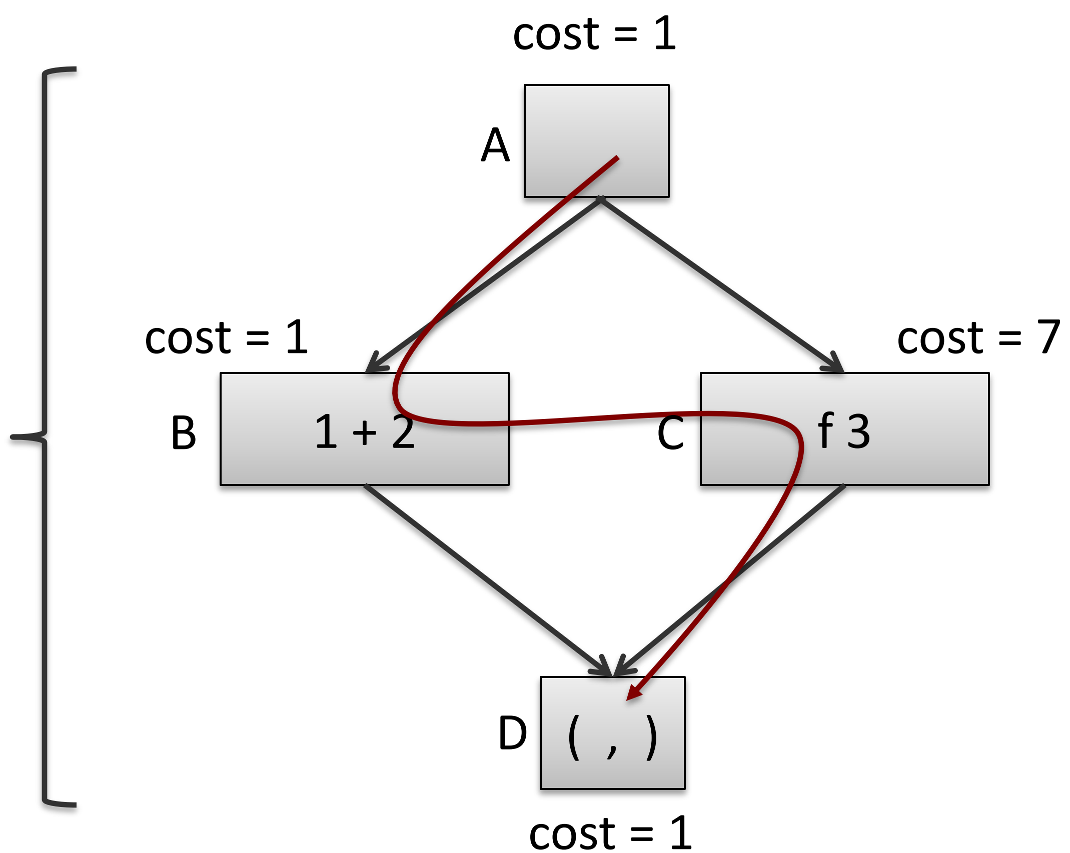
(1 + 2 || f 3)



Suppose we have 1 processor. How much time does this computation take?

Visualizing Computational Costs

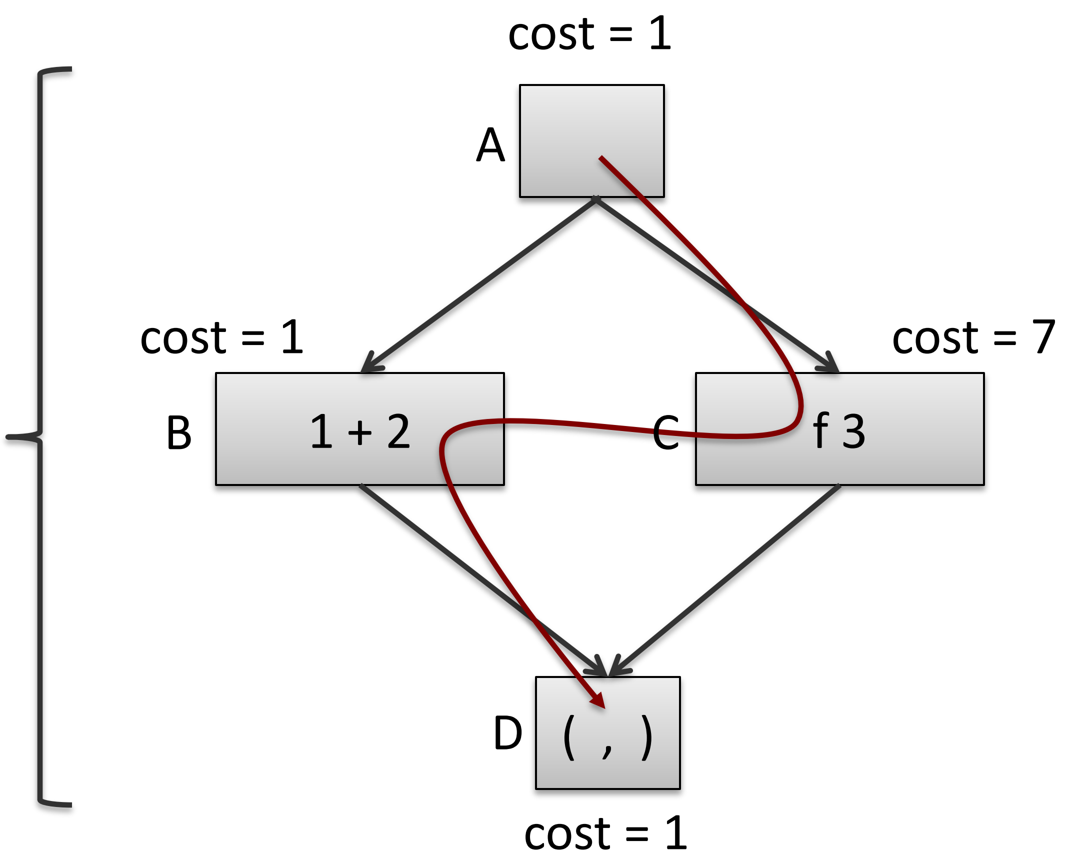
(1 + 2 || f 3)



Suppose we have 1 processor. How much time does this computation take?
Schedule A-B-C-D: 1 + 1 + 7 + 1

Visualizing Computational Costs

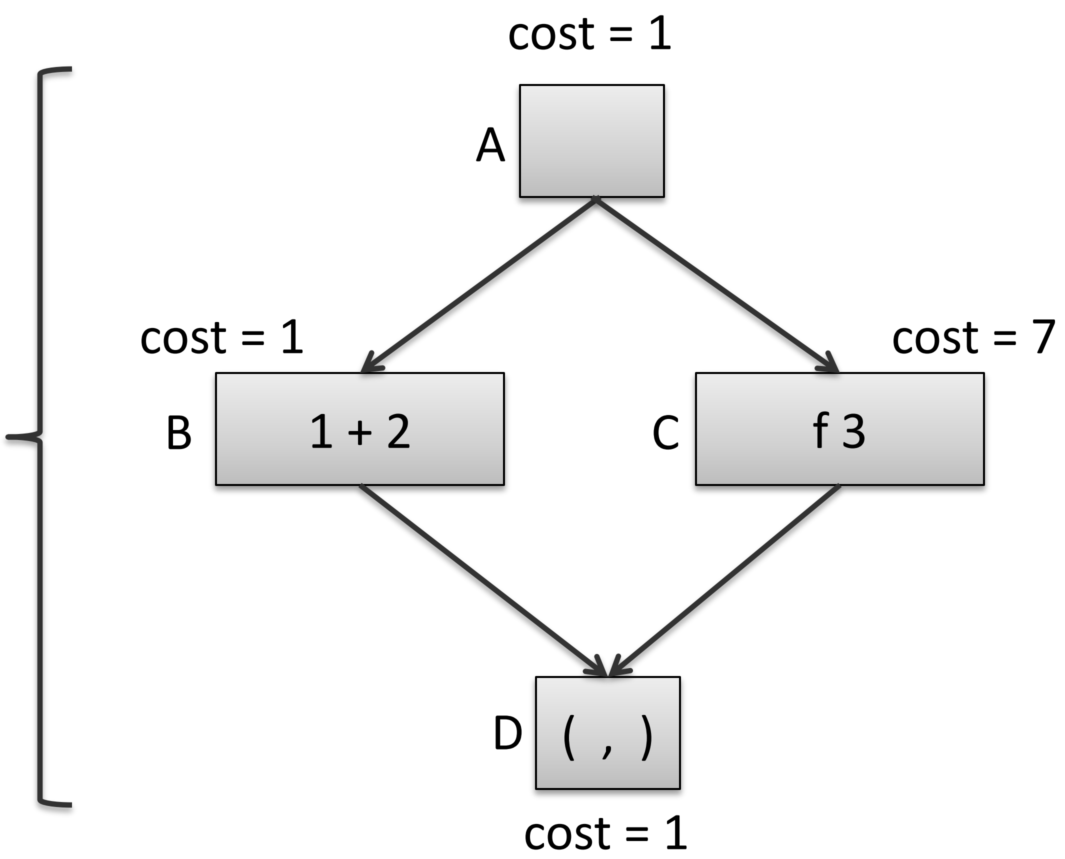
(1 + 2 || f 3)



Suppose we have 1 processor. How much time does this computation take?
Schedule A-C-B-D: 1 + 1 + 7 + 1

Visualizing Computational Costs

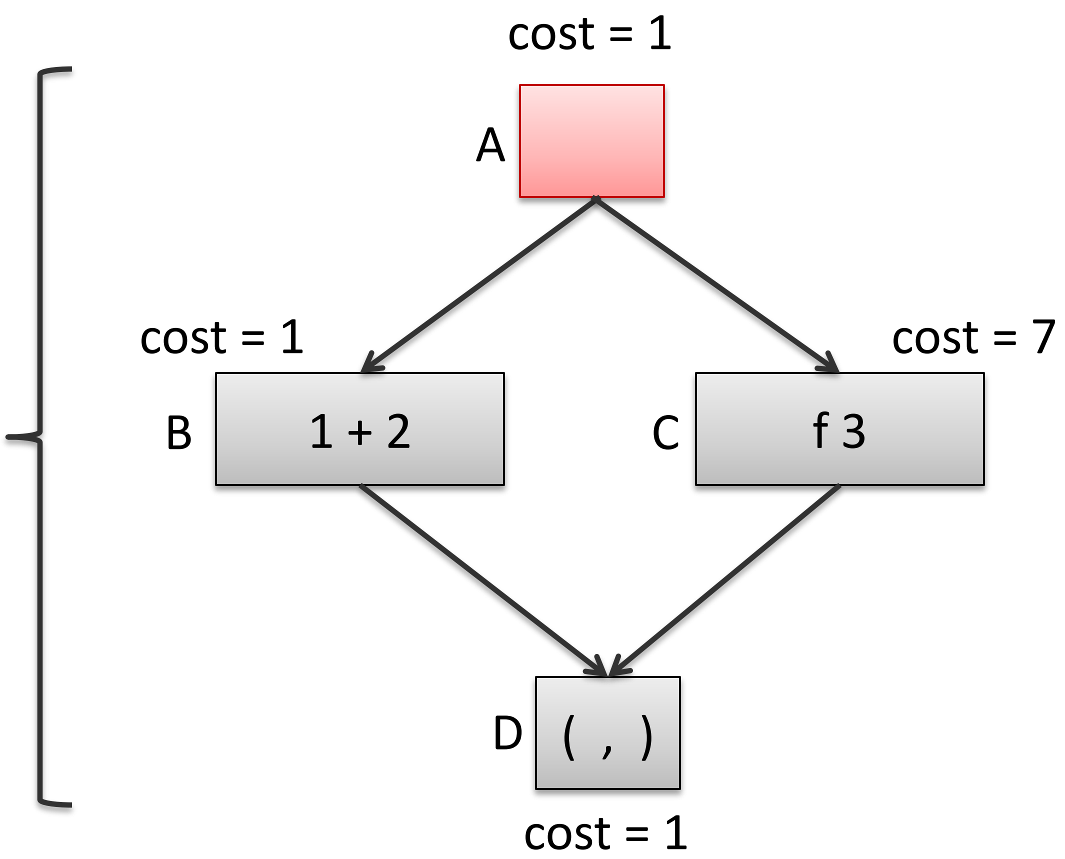
(1 + 2 || f 3)



Suppose we have 2 processors. How much time does this computation take?

Visualizing Computational Costs

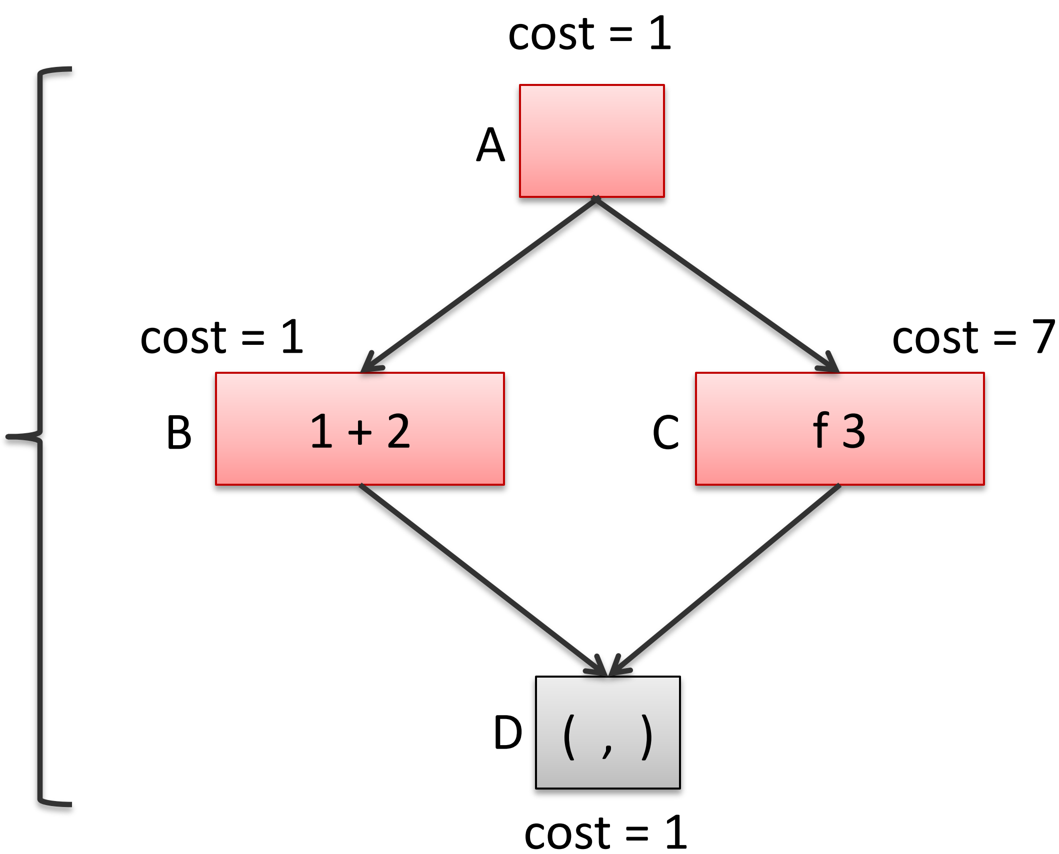
(1 + 2 || f 3)



Suppose we have 2 processors. How much time does this computation take?
Cost so far: 1

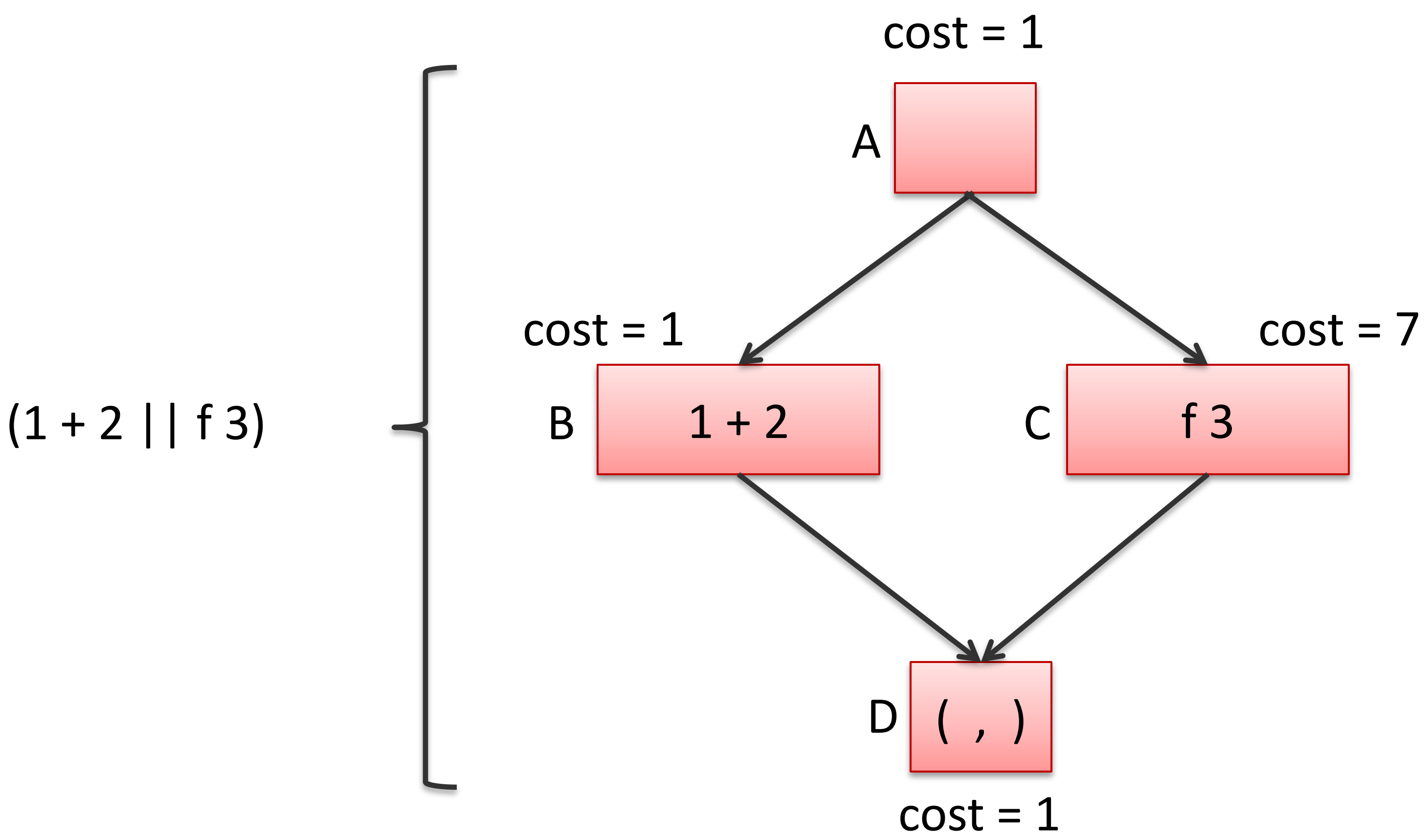
Visualizing Computational Costs

(1 + 2 || f 3)



Suppose we have 2 processors. How much time does this computation take?
Cost so far: 1 + max(1,7)

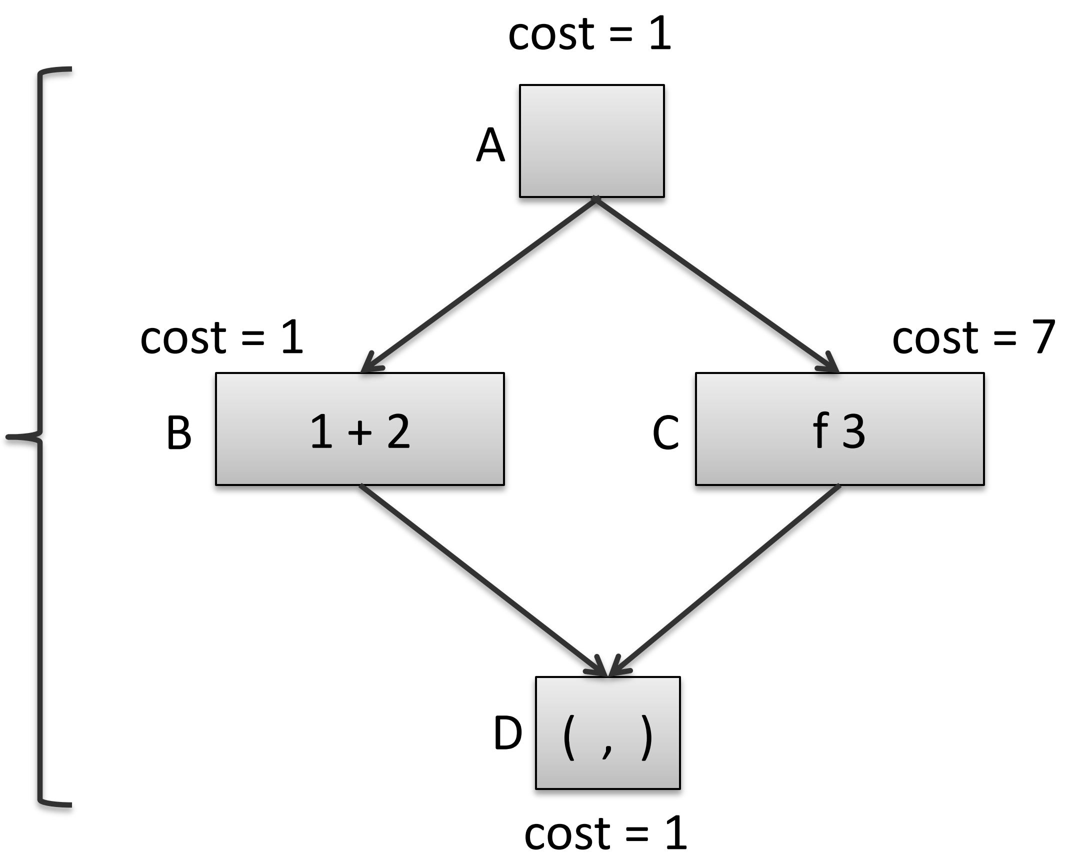
Visualizing Computational Costs



Suppose we have 2 processors. How much time does this computation take?
Cost so far: 1 + max(1,7) + 1

Visualizing Computational Costs

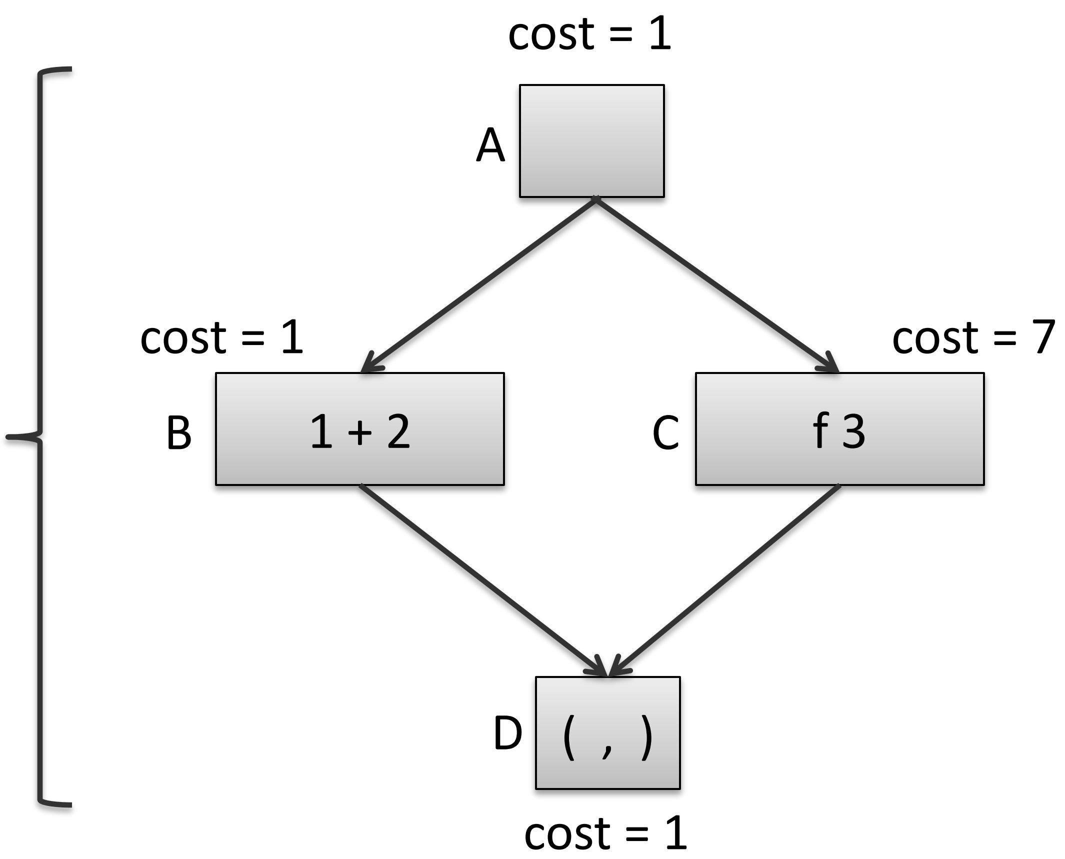
(1 + 2 || f 3)



Suppose we have 2 processors. How much time does this computation take?
Total cost: 1 + max(1,7) + 1. We say the *schedule* we used was: A-CB-D

Visualizing Computational Costs

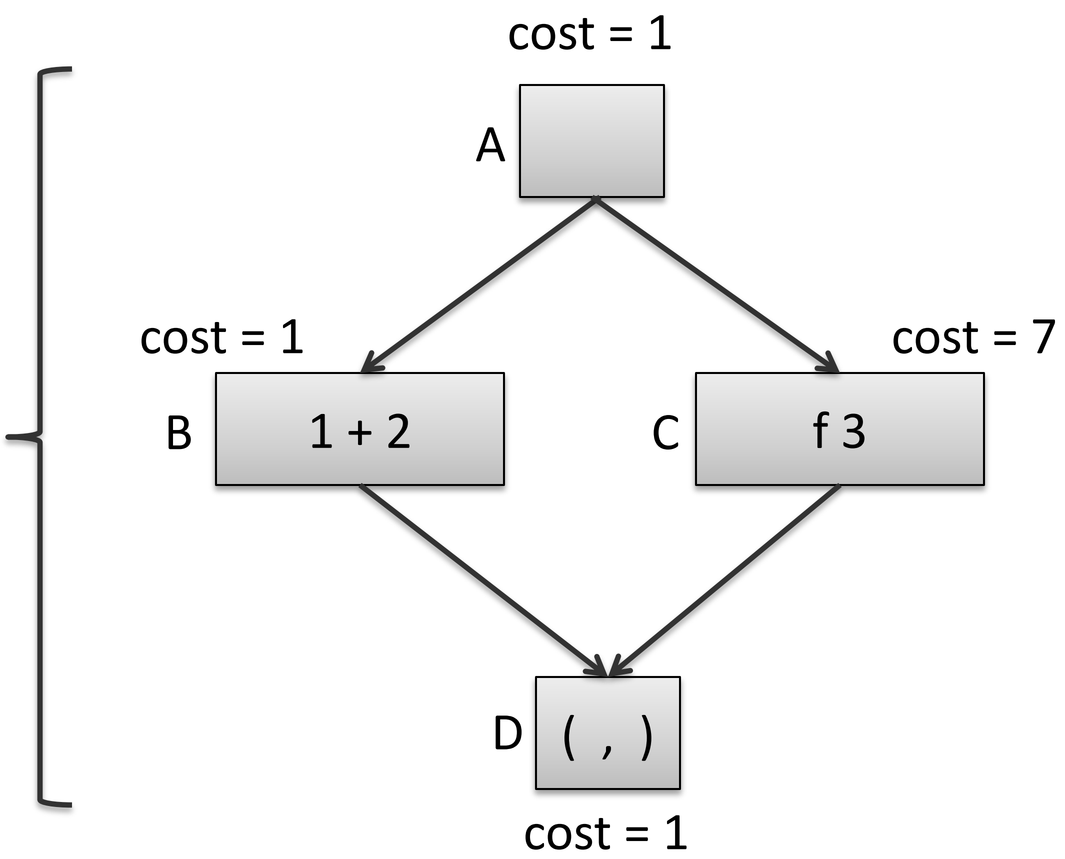
(1 + 2 || f 3)



Suppose we have 3 processors. How much time does this computation take?

Visualizing Computational Costs

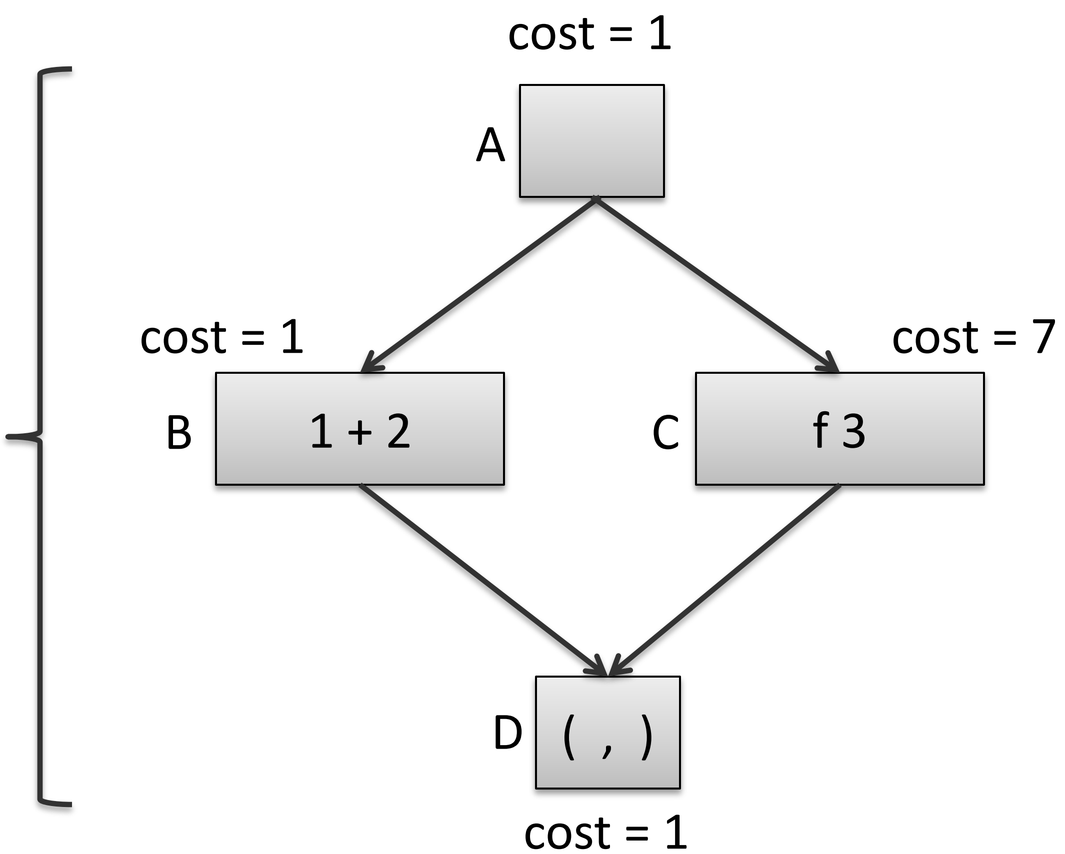
(1 + 2 || f 3)



Suppose we have 3 processors. How much time does this computation take?
Schedule A-BC-D: 1 + max(1,7) + 1 = 9

Visualizing Computational Costs

(1 + 2 || f 3)



Suppose we have infinite processors. How much time does this computation take?

Schedule A-BC-D: 1 + max(1,7) + 1 = 9

Work and Span

Understanding the complexity of a parallel program is a little more complex than a sequential program

- the number of processors has a significant effect

One way to *approximate* the cost is to consider a parallel algorithm independently of the machine it runs on is to consider *two* metrics:

- Work: The cost of executing a program with just 1 processor.
- Span: The cost of executing a program with an infinite number of processors

Always good to minimize work

- Every instruction executed consumes energy
- Minimize span as a second consideration
- Communication costs are also crucial (we are ignoring them)

Parallelism

The parallelism of an algorithm is an estimate of the maximum number of processors an algorithm can profit from.

- parallelism = work / span

If work = span then parallelism = 1.

- We can only use 1 processor
- It's a sequential algorithm

If span = ½ work then parallelism = 2

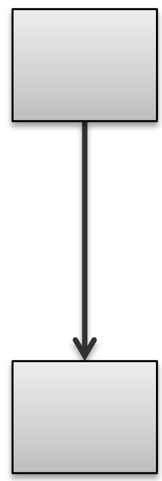
- We can use up to 2 processors

If work = 100, span = 1

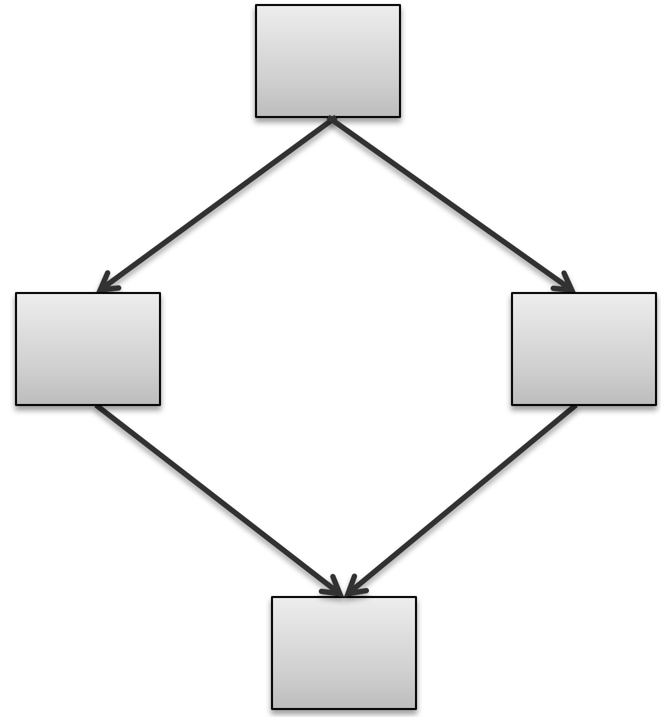
- All operations are independent & can be executed in parallel
- We can use up to 100 processors

Series-Parallel Graphs

one operation



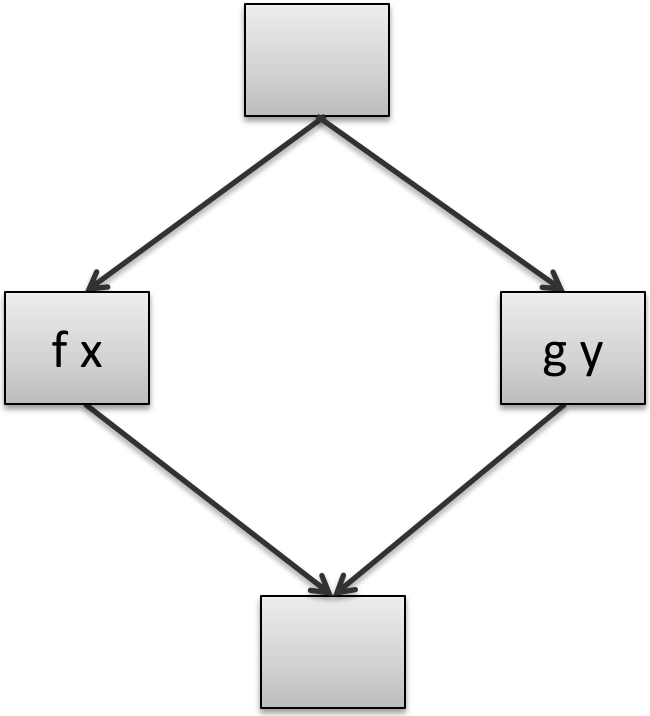
two operations
in sequence
e1; e2



two operations
in parallel
(e1 || e2)

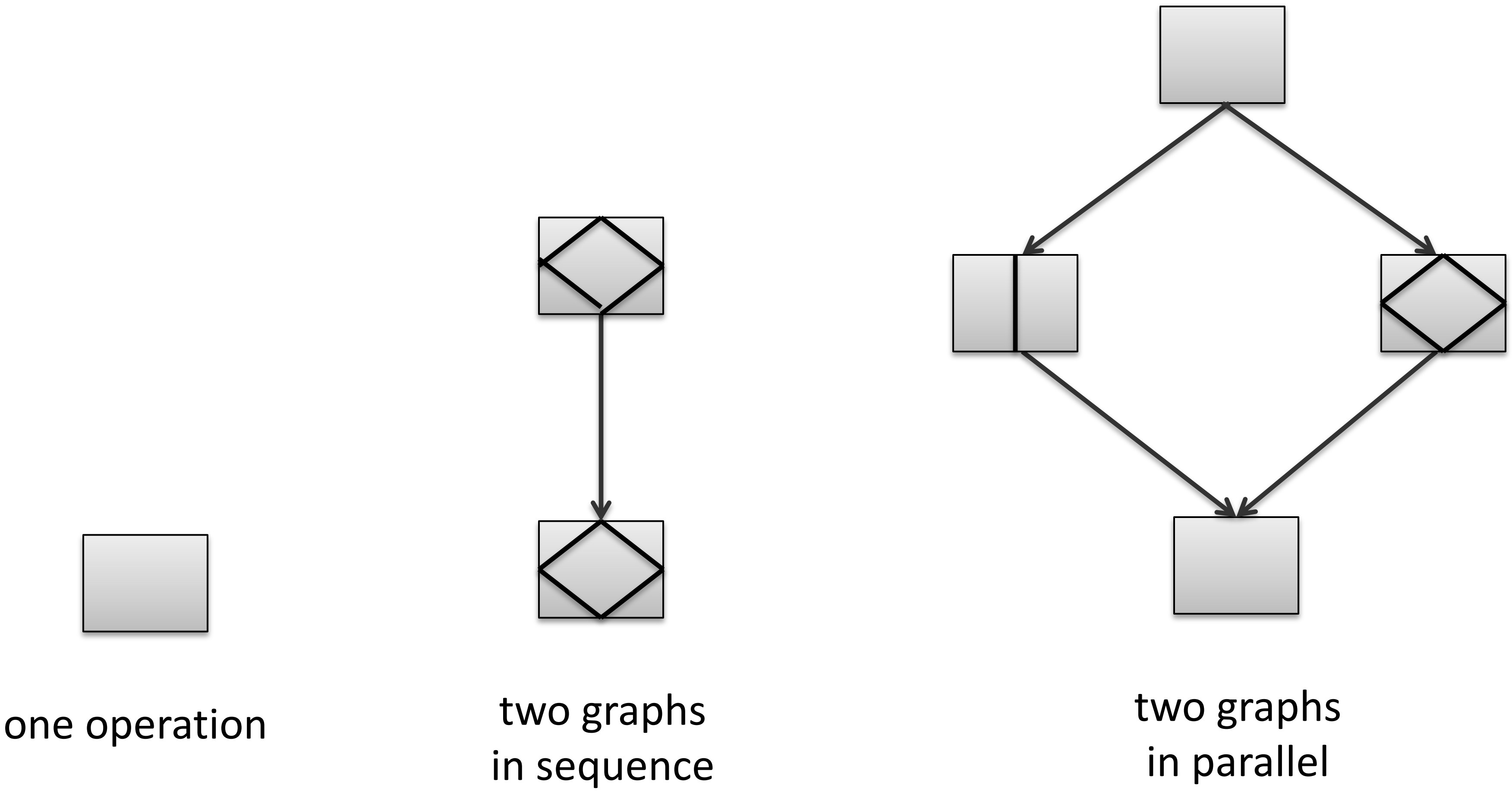
Series-parallel graphs arise from execution of functional programs with parallel pairs. Also known as well-structured, nested parallelism.

Parallel Pairs




```
let both f x g y =
  let ff = future f x in
  let gv = g y in
  (force ff, gv)
```

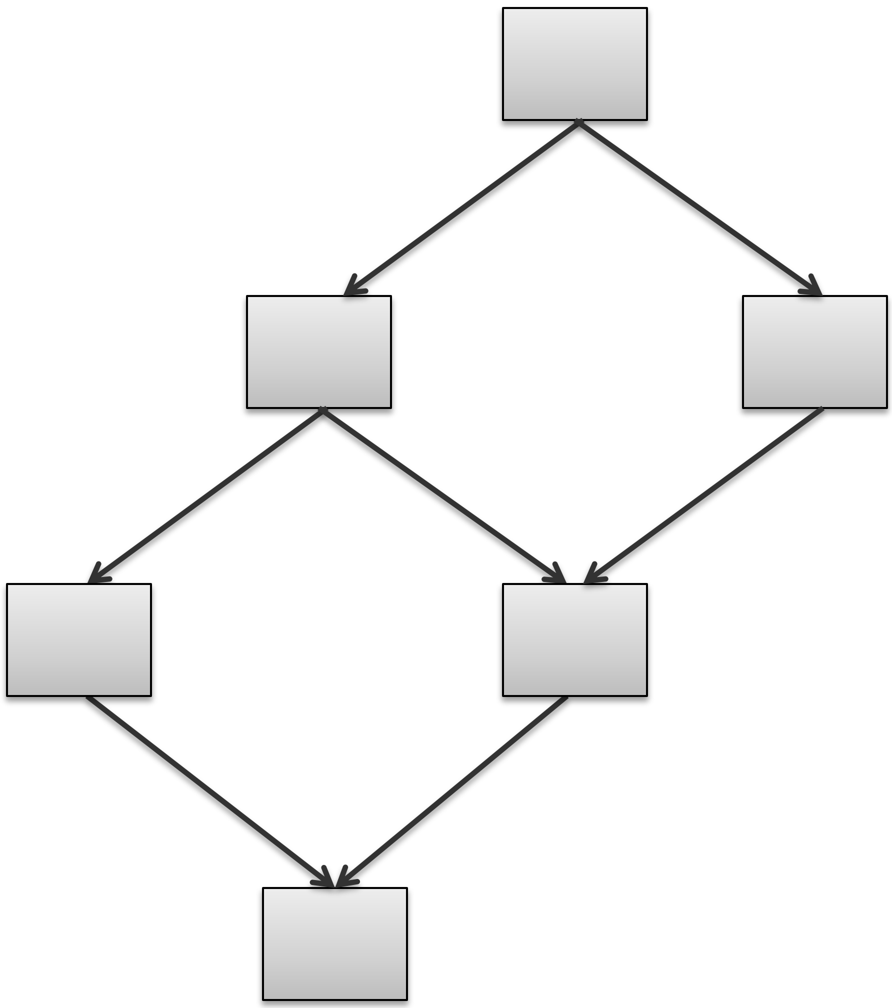
Series-Parallel Graphs Compose



In general, a series-parallel graph has a source and a sink and is:

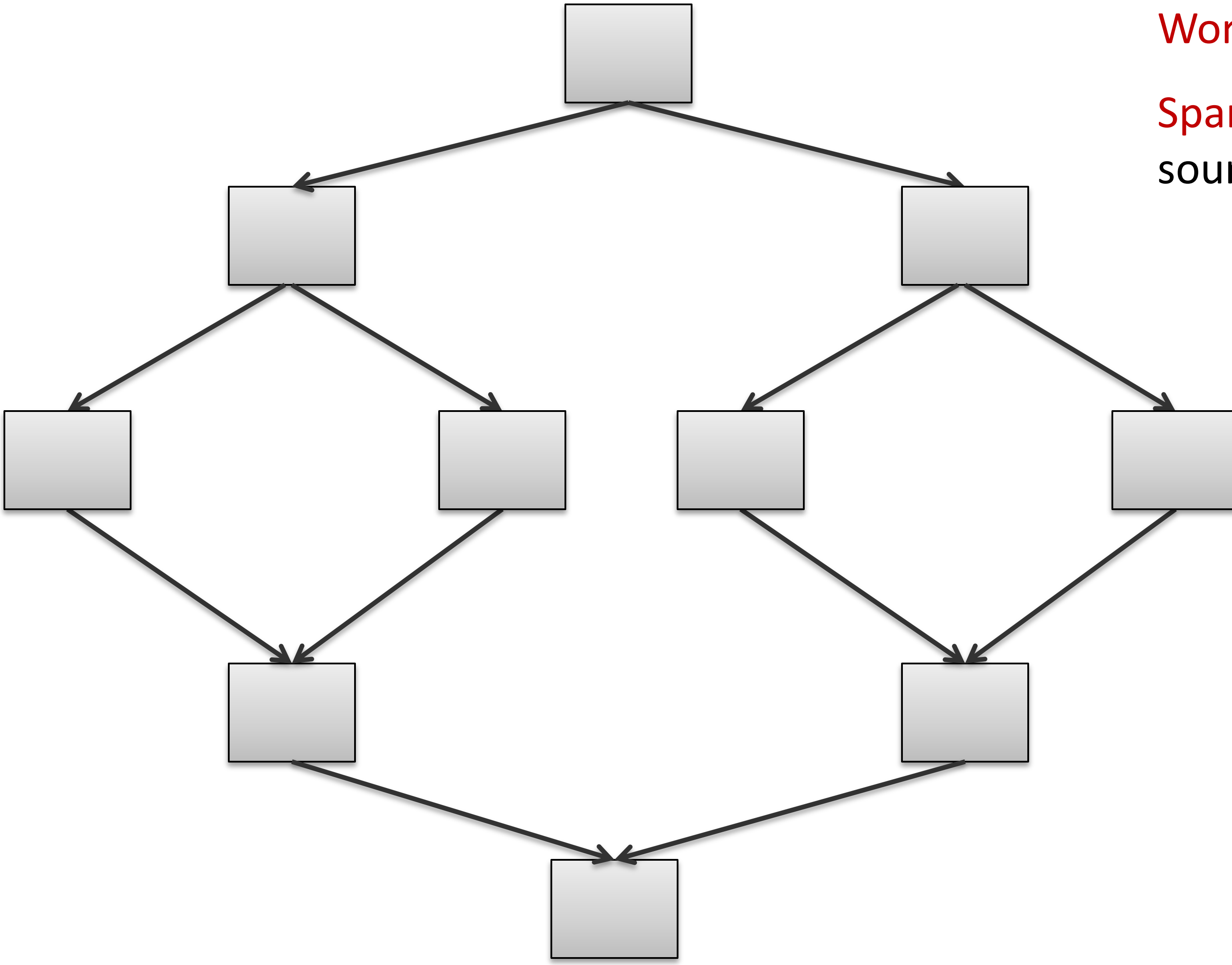
- a single node, or
- two series-parallel graphs in sequence, or
- two series-parallel graphs in parallel

Not a Series-Parallel Graph



However:
The results about greedy schedulers (next few slides) do apply to DAG schedules as well as series-parallel schedules!

Work and Span of Acyclic Graphs

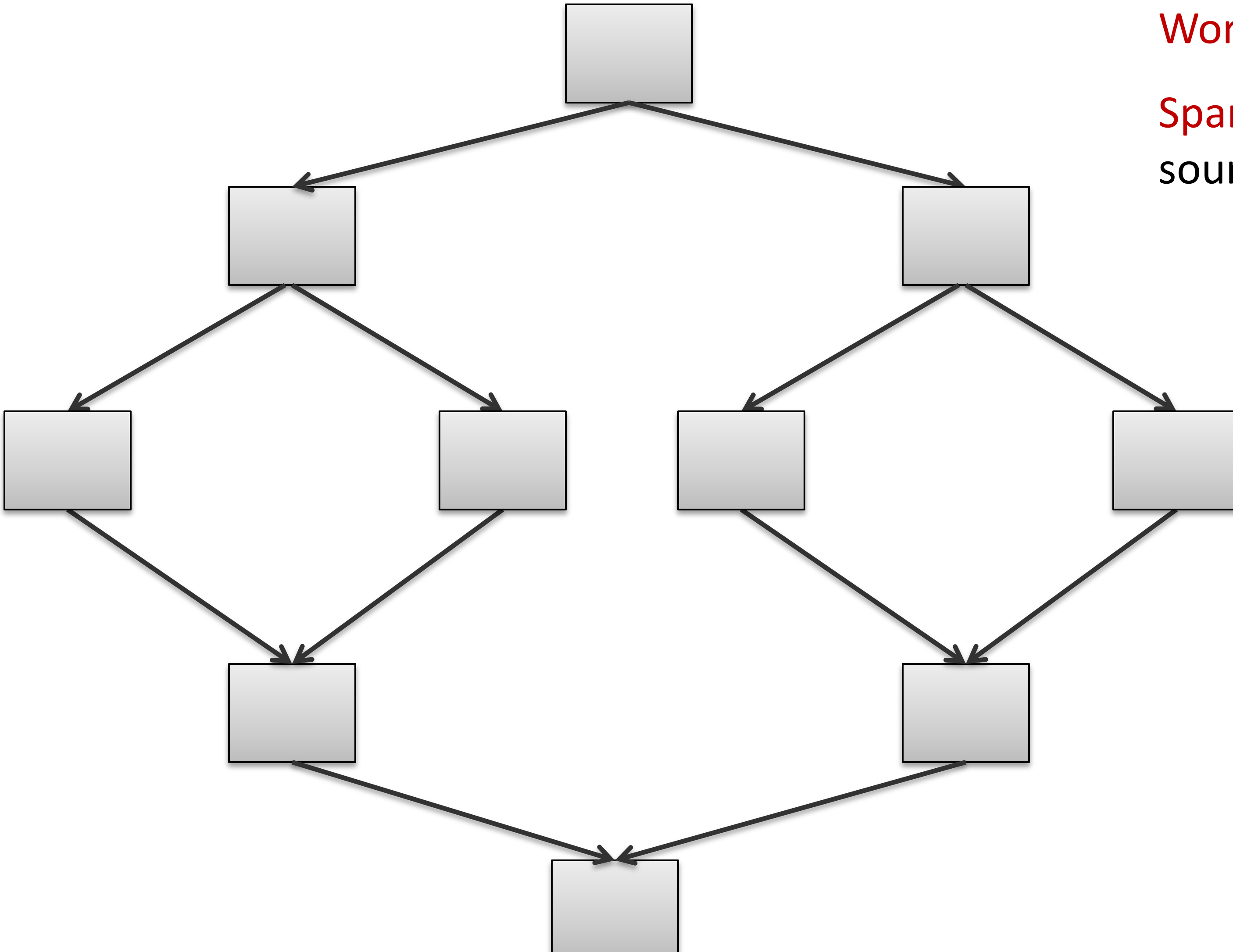


Let's assume each node costs 1.

Work: sum the nodes.

Span: longest path from source to sink.

Work and Span of Acyclic Graphs



Let's assume each node costs 1.

Work: sum the nodes.

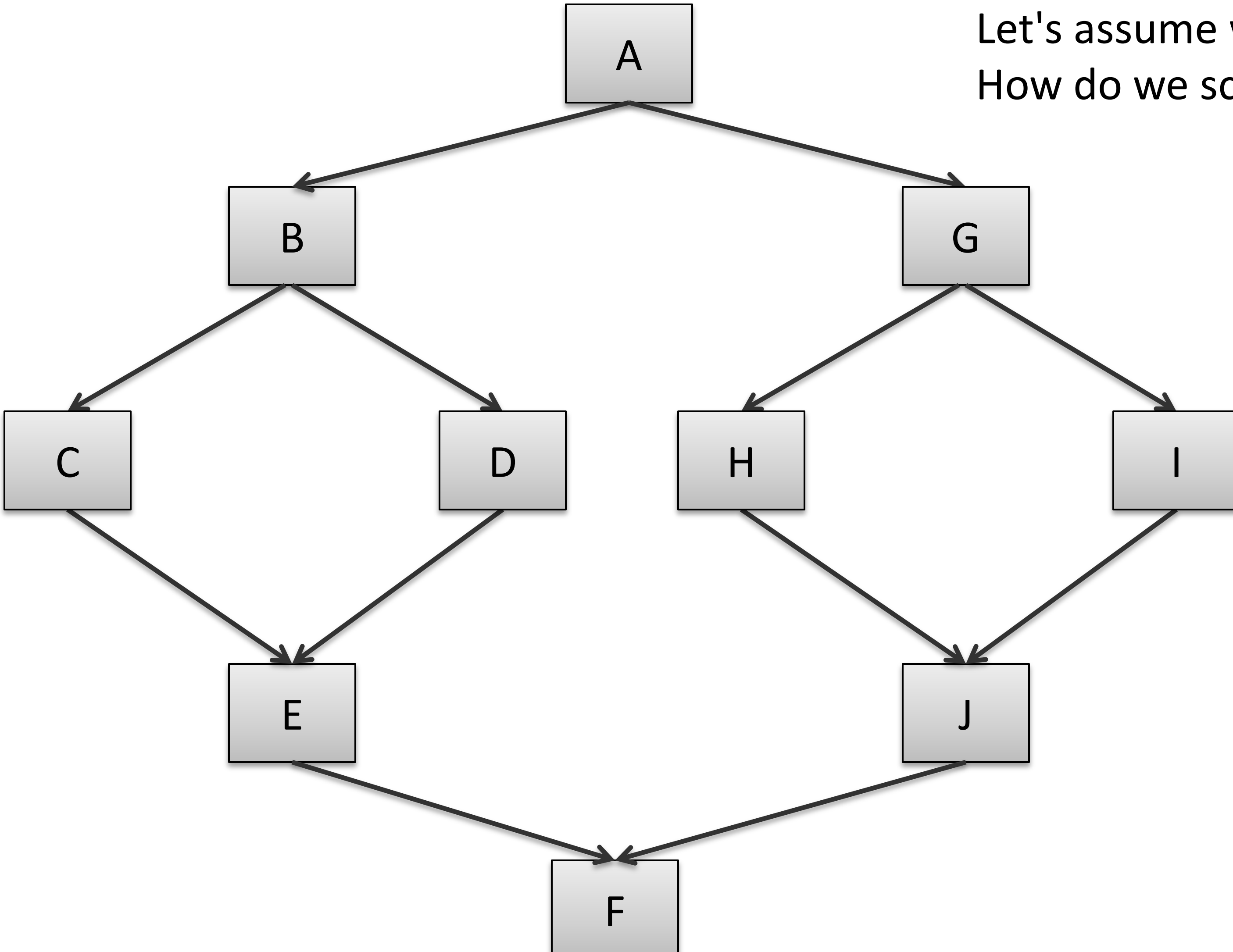
Span: longest path from source to sink.

work = 10
span = 5

Scheduling

Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?



Scheduling

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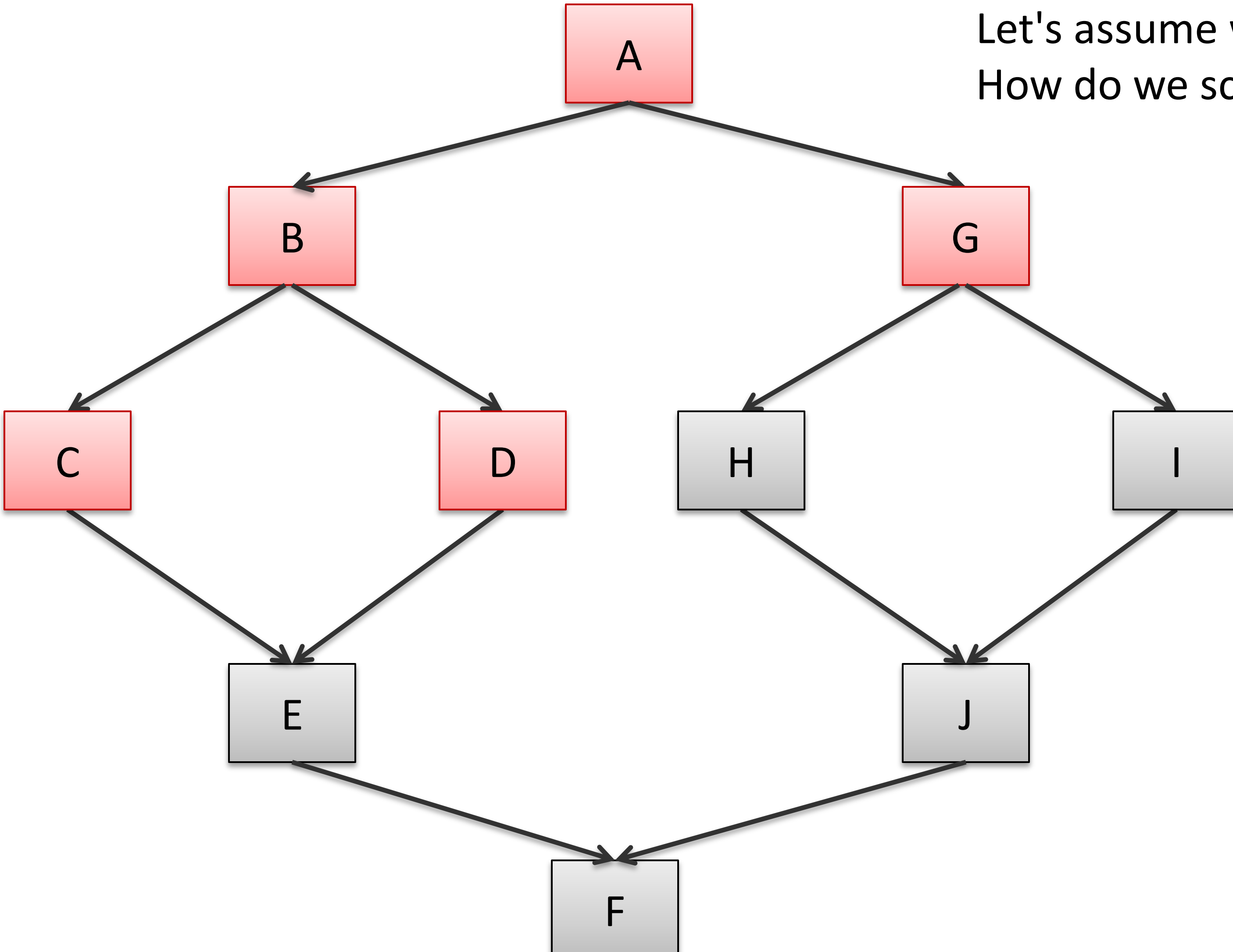
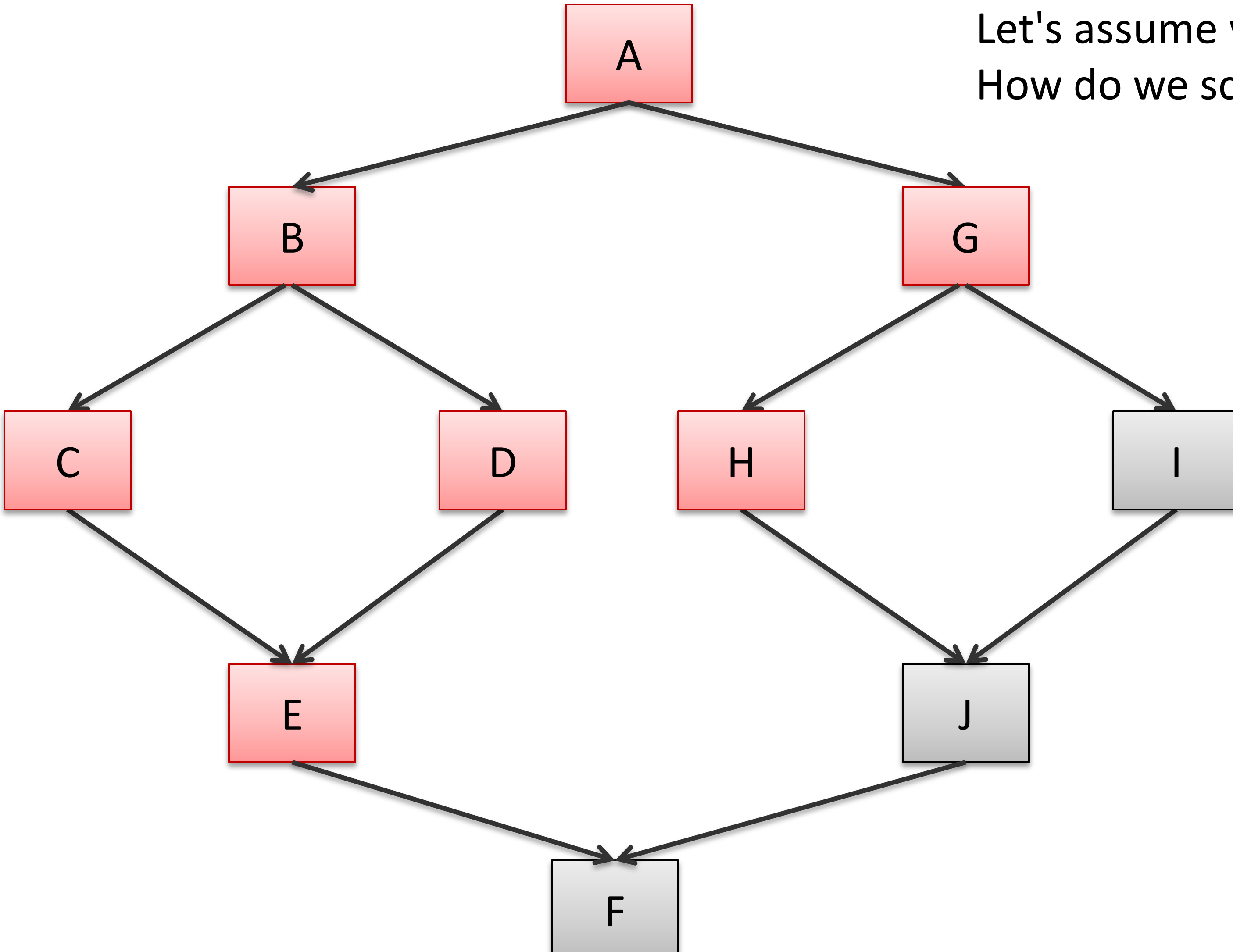


Option 1:
A
B G
C D

Scheduling

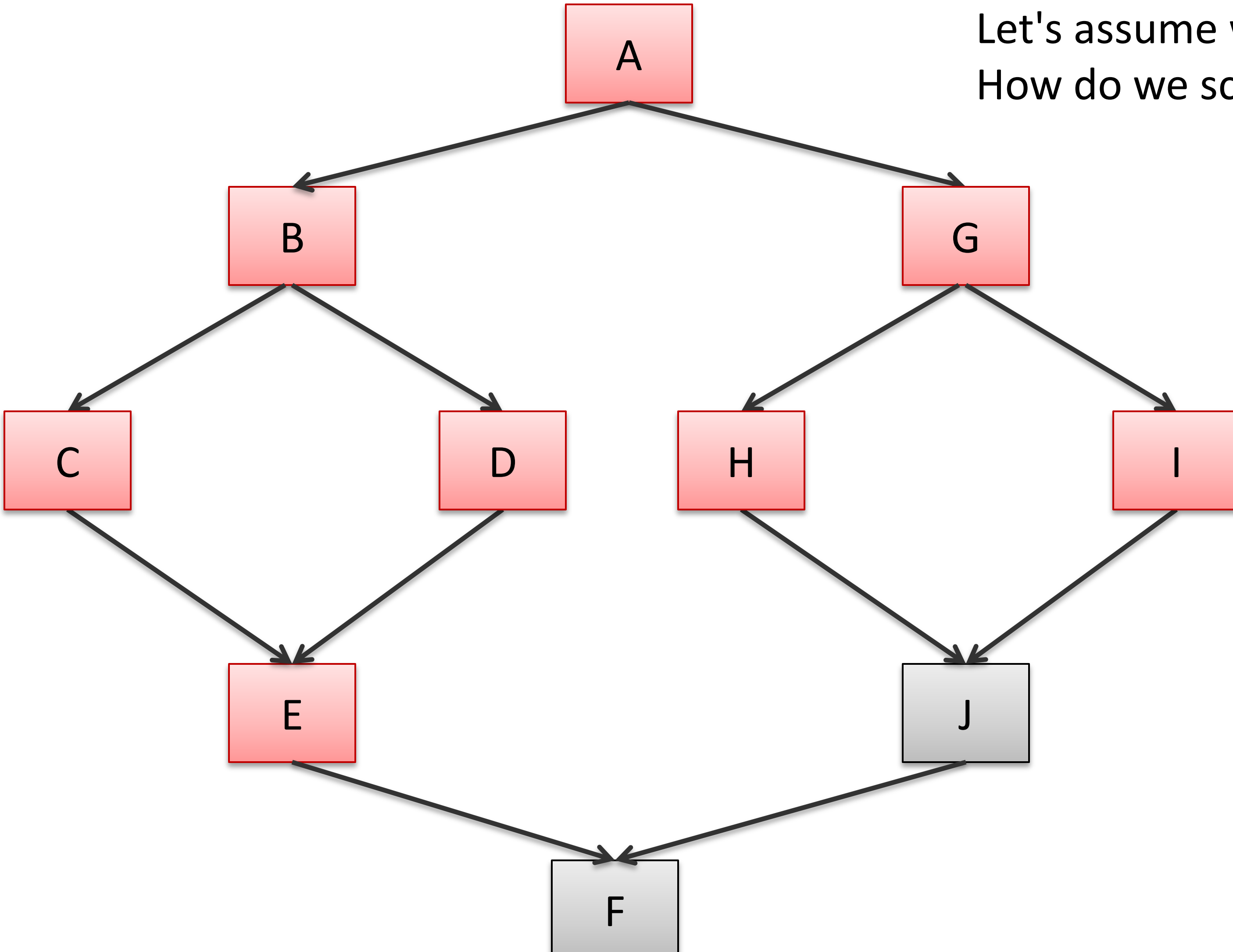


Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?

Option 1:
A
B G
C D
E H

Scheduling

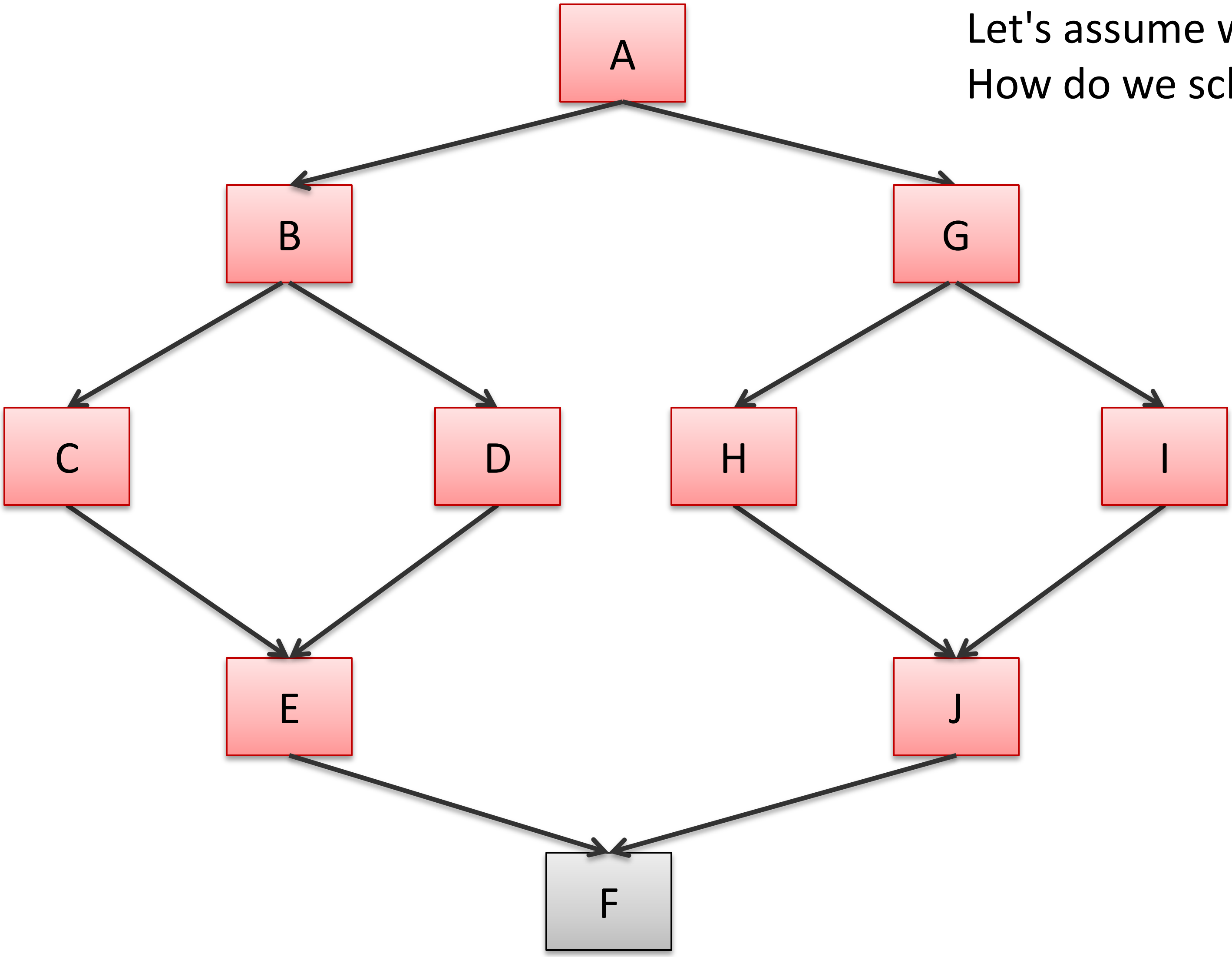


Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?

Option 1:
A
B G
C D
E H
I

Scheduling

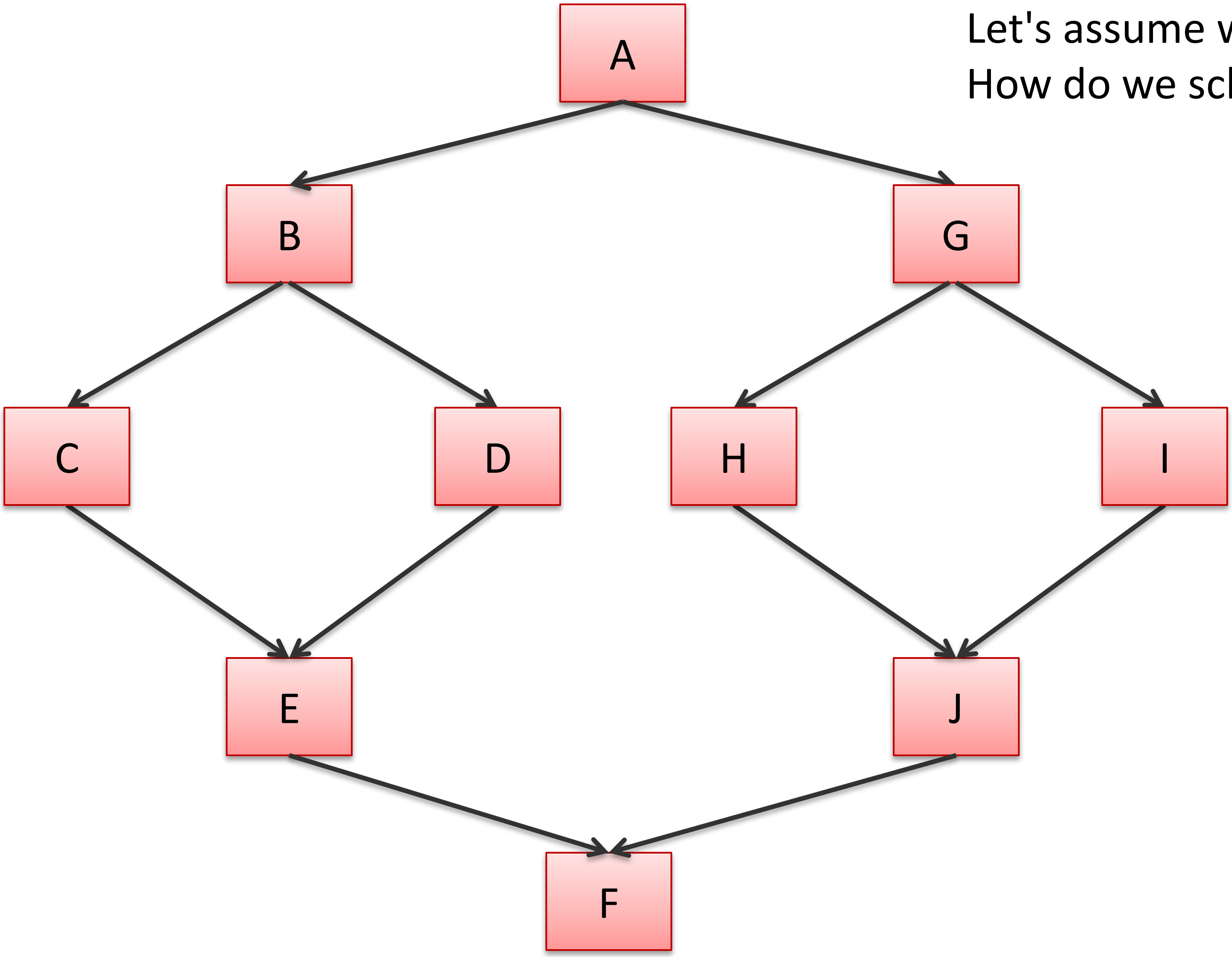


Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?

Option 1:
A
B G
C D
E H
I
J

Scheduling

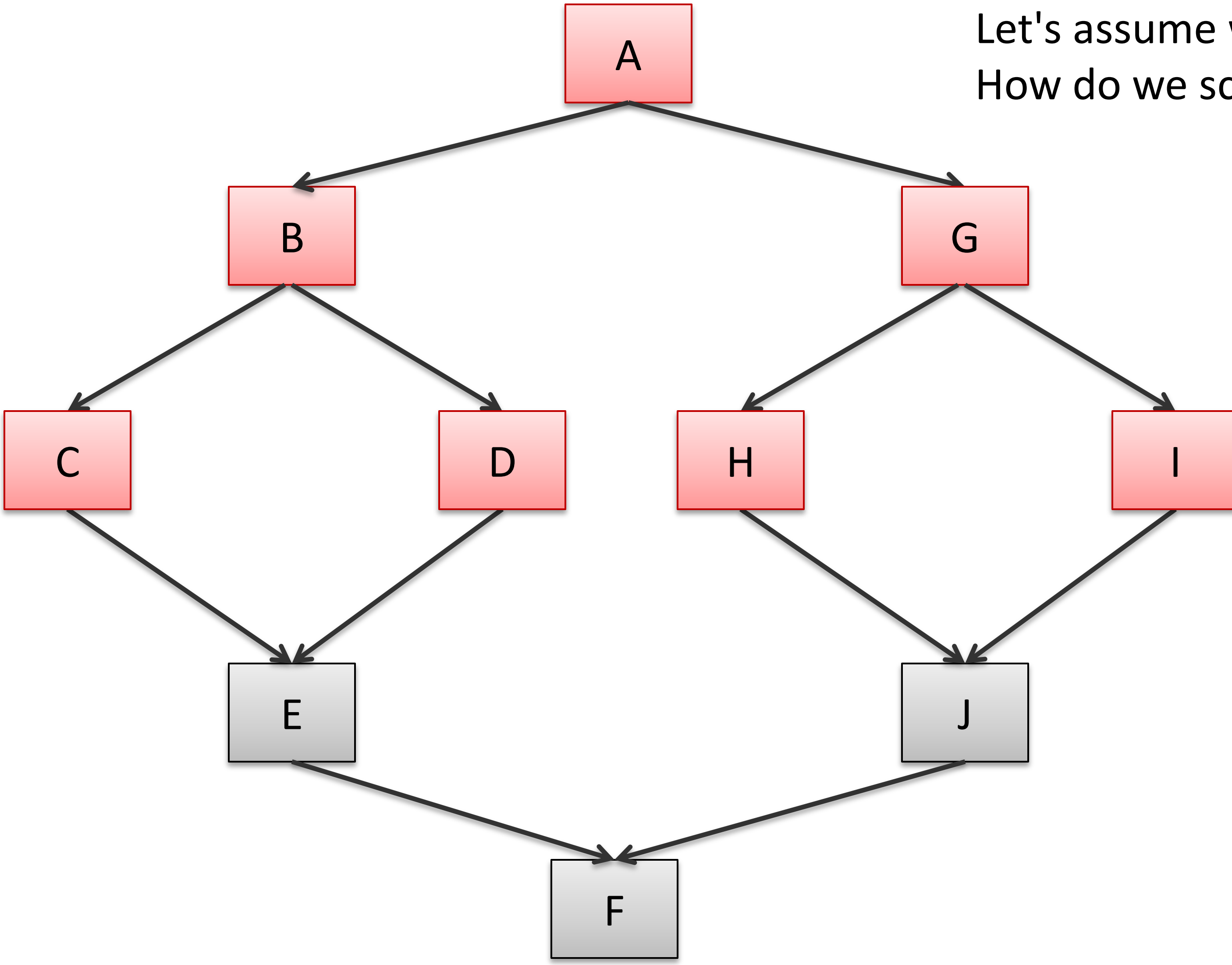


Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?

Option 1:
A
B G
C D
E H
I
J
F

Scheduling

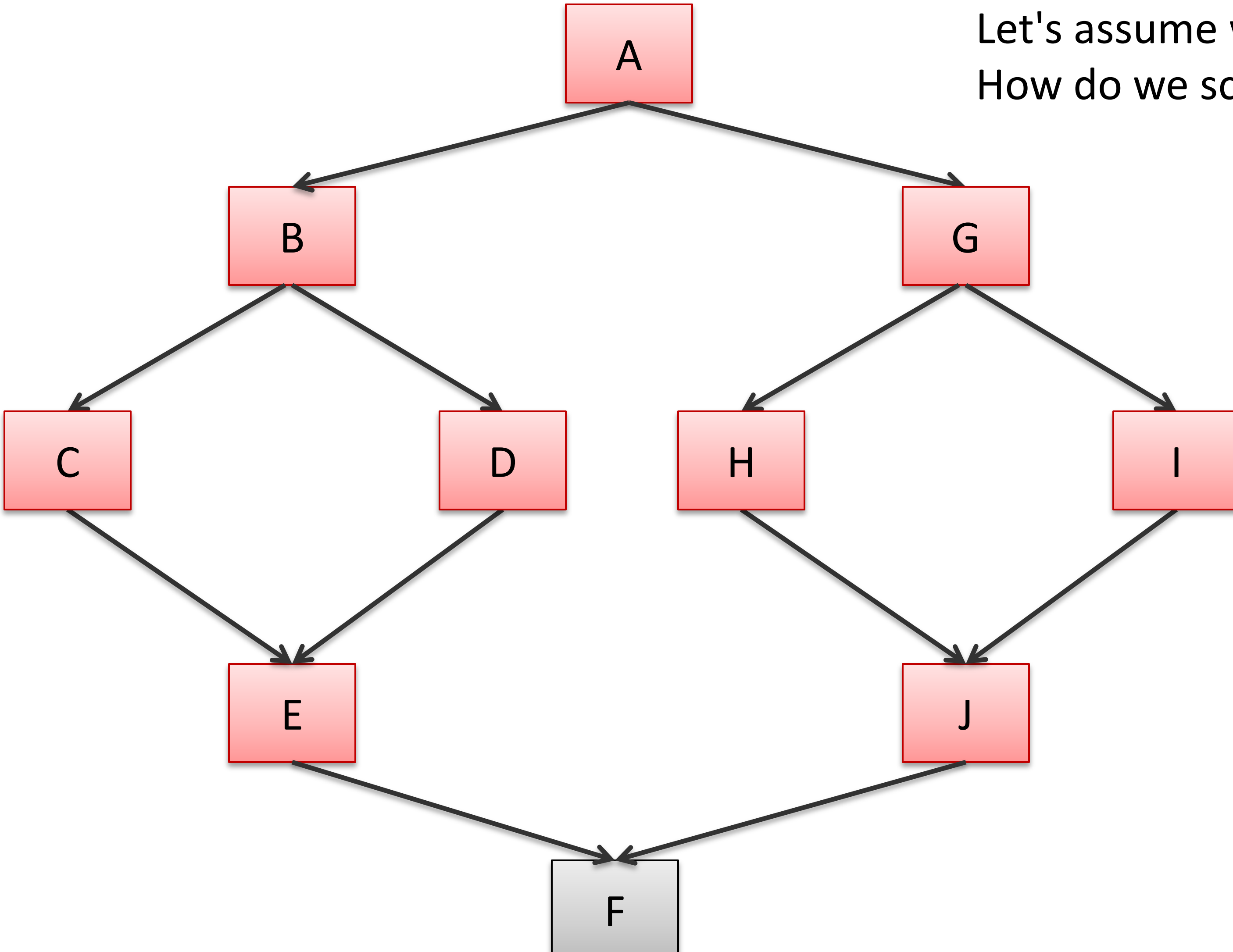


Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?

Option 1:
A
B G
C D
~~E H~~ H I
~~I~~
~~J~~
~~F~~

Scheduling



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Let's assume we have 2 processors.
How do we schedule computation?

Option 1:

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B G

C D

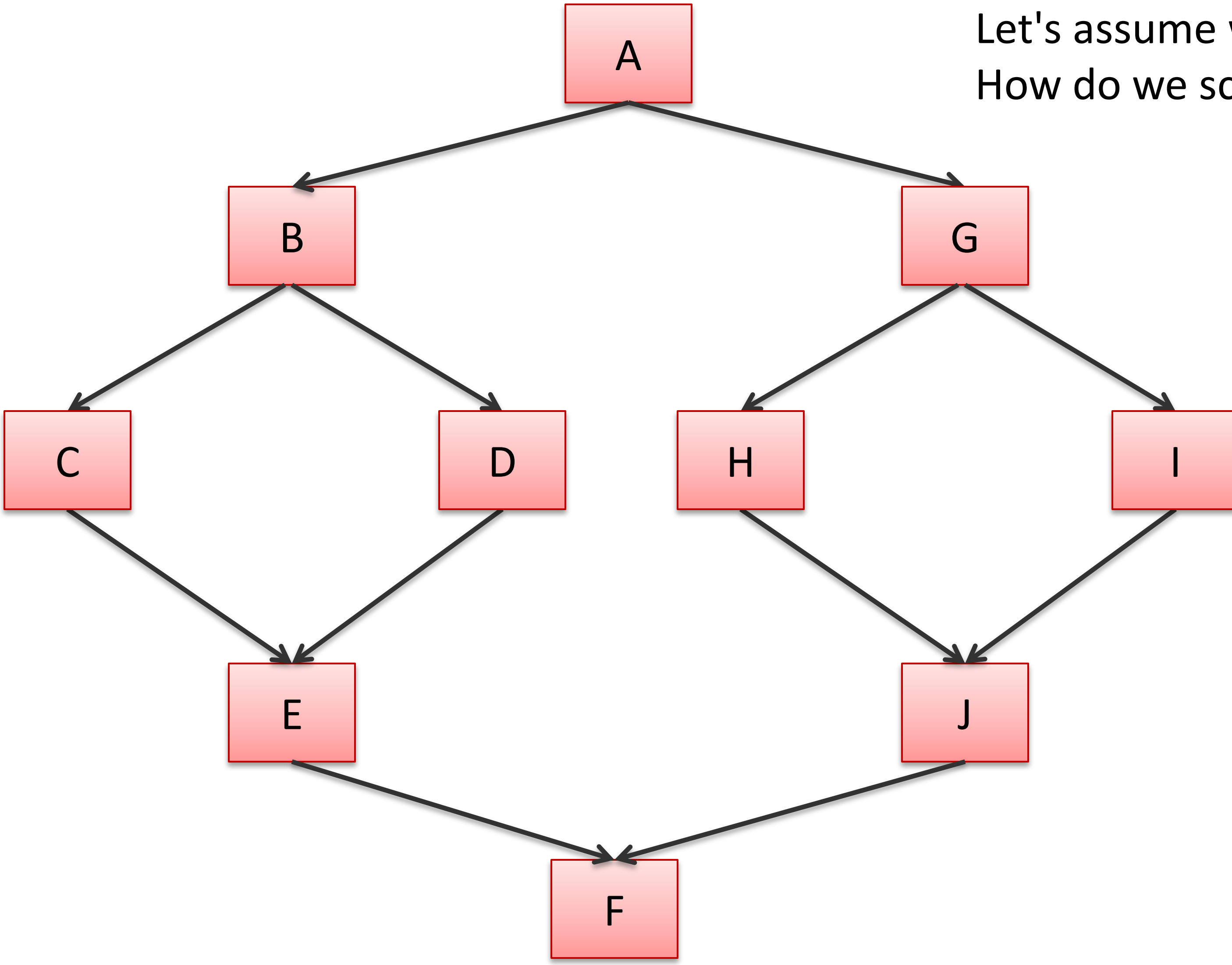
~~E H~~ H I

~~I~~ E J

~~J~~

~~F~~

Scheduling



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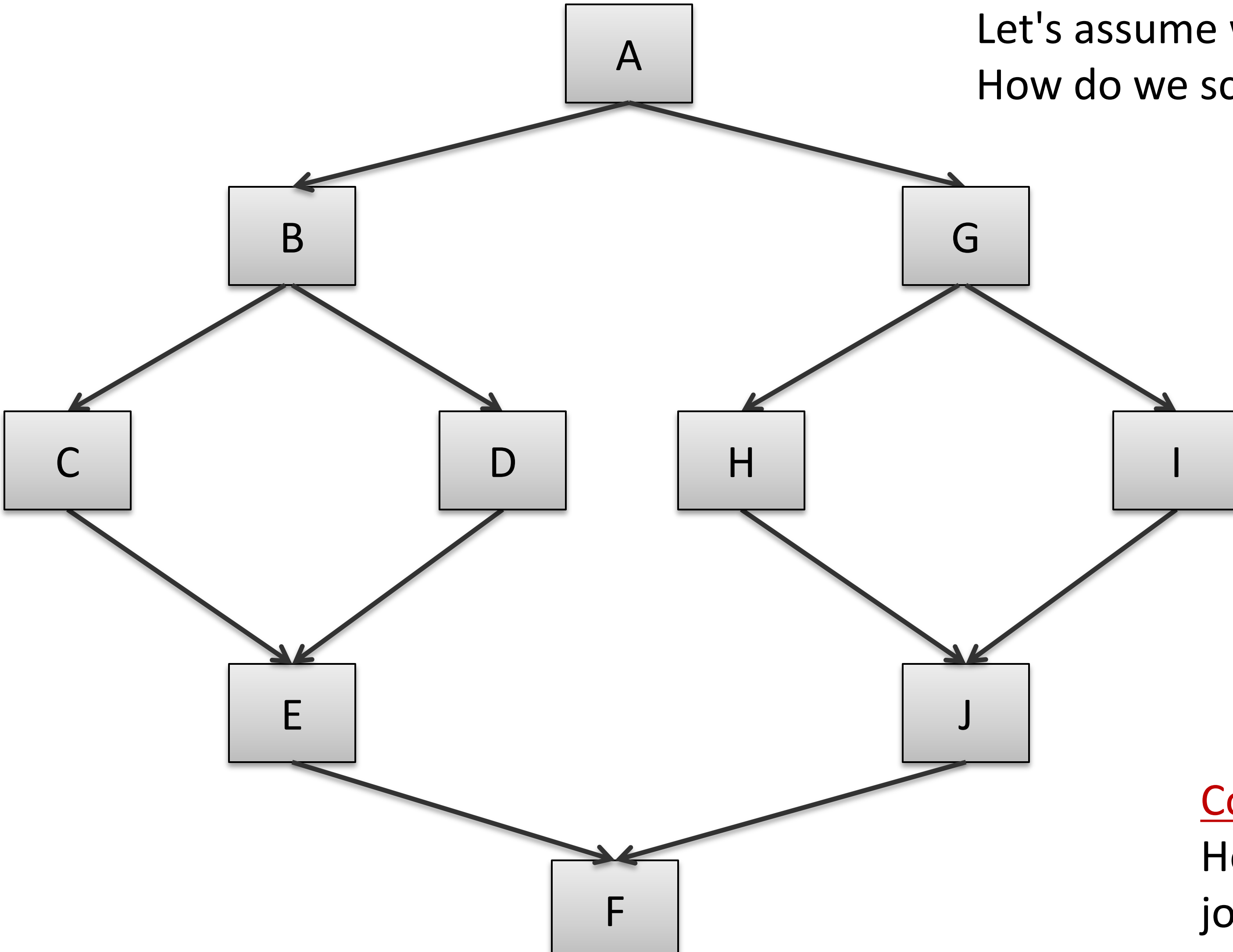
How do we schedule computation?

Option 1:

A	
B G	
C D	
~~E H~~	H I
~~I~~	E J
~~J~~	F
~~F~~	

Scheduling



Let's assume each node costs 1.

Let's assume we have 2 processors.
How do we schedule computation?

Option 1:

A	
B G	
C D	
~~E H~~	H I
~~I~~	E J
~~J~~	F
~~F~~	

Conclusion:

How you schedule jobs can have an impact on performance

Greedy Schedulers

Greedy schedulers will schedule some task to a processor as soon as that processor is free.

- Doesn't sound so smart!

Greedy Schedulers

Greedy schedulers will schedule some task to a processor as soon as that processor is free.

- Doesn't sound so smart!

Properties (for p processors):

- T(p) < work/p + span
  - won't be worse than dividing up the data perfectly between processors, except for the last little bit, which causes you to add the span on top of the perfect division
- T(p) >= max(work/p, span)
  - can't do better than perfect division between processors (work/p)
  - can't be faster than span

Greedy Schedulers

Properties (for p processors):

max(work/p, span) <= T(p) < work/p + span

Consequences:

- as span gets small relative to work/p
  - work/p + span ==> work/p
  - max(work/p, span) ==> work/p
  - so T(p) ==> work/p -- greedy schedulers converge to the optimum!
- if span approaches the work
  - work/p + span ==> span
  - max(work/p, span) ==> span
  - so T(p) ==> span – greedy schedulers converge to the optimum!

And therefore

Even though greedy schedulers are simple to implement,

they can be effective in building a parallel programming system.

and

This *supports* the idea that **work and span** are useful ways to reason about the cost of parallel programs.

PARALLEL SEQUENCES

Parallel Sequences

Parallel sequences

< e1 , e2 , e3 , ... , en >

Operations:

- creation (called **tabulate**)
- indexing an element in constant span
- map
- scan -- like a fold: <u, u + e1, u + e1 + e2, ...> log n span!

Languages:

- Nesl [Blelloch]
- Data-parallel Haskell

Parallel Sequences: Selected Operations

```
tabulate : (int -> 'a) -> int -> 'a seq

tabulate f n  == <f 0, f 1, ..., f (n-1)>
work = O(n)          span = O(1)
```

Parallel Sequences: Selected Operations

```
tabulate : (int -> 'a) -> int -> 'a seq

tabulate f n  == <f 0, f 1, ..., f (n-1)>
work = O(n)          span = O(1)
```

```
nth : 'a seq -> int -> 'a

nth <e0, e1, ..., e(n-1)> i == ei
work = O(1)          span = O(1)
```

Parallel Sequences: Selected Operations

```
tabulate : (int -> 'a) -> int -> 'a seq

tabulate f n  == <f 0, f 1, ..., f (n-1)>
work = O(n)          span = O(1)
```

```
nth : 'a seq -> int -> 'a

nth <e0, e1, ..., e(n-1)> i == ei
work = O(1)          span = O(1)
```

```
length : 'a seq -> int

length <e0, e1, ..., e(n-1)> == n
work = O(1)          span = O(1)
```

Example Problems

Write a function that creates the sequence <0, ..., n-1>

with Span = O(1) and Work = O(n).

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function that creates the sequence <0, ..., n-1>

with Span = O(1) and Work = O(n).

```
(* create n == <0, 1, ..., n-1> *)
let create n =
```

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function that creates the sequence <0, ..., n-1>

with Span = O(1) and Work = O(n).

```
(* create n == <0, 1, ..., n-1> *)
let create n =
  tabulate (fun i -> i) n
```

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function such that given a sequence <v0, ..., vn-1>, maps f over each element of the sequence with Span = O(1) and Work = O(n), returning the new sequence (if f is constant work)

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function such that given a sequence <v0, ..., vn-1>, maps f over each element of the sequence with Span = O(1) and Work = O(n), returning the new sequence (if f is constant work)

```
(* map f <v0, ..., vn-1> == <f v0, ..., f vn-1> *)
let map f s =
```

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function such that given a sequence <v0, ..., vn-1>, maps f over each element of the sequence with Span = O(1) and Work = O(n), returning the new sequence (if f is constant work)

```
(* map f <v0, ..., vn-1> == <f v0, ..., f vn-1> *)
let map f s =
  tabulate (fun i -> f (nth s i)) (length s)
```

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function such that given a sequence <v0, ..., vn-1>, reverses the sequence. with Span = O(1) and Work = O(n)

Operations:

	Work	Span
`tabulate f n`	n	1
`nth i s`	1	1
`length s`	1	1

Example Problems

Write a function such that given a sequence <v0, ..., vn-1>, reverses the sequence. with Span = O(1) and Work = O(n)

```
(* reverse <v0, ..., vn-1> == <vn-1, ..., v0> *)
let reverse s =
```

Operations:

	Work	Span
`tabulate f n`	`n`	`1`
`nth i s`	`1`	`1`
`length s`	`1`	`1`

Example Problems

Write a function such that given a sequence <v0, ..., vn-1>, reverses the sequence. with Span = O(1) and Work = O(n)

```
(* reverse <v0, ..., vn-1> == <vn-1, ..., v0> *)
let reverse s =
  let n = length s in
  tabulate (fun i -> nth s (n-i-1)) n
```

Operations:

	Work	Span
tabulate f n	n	1
nth i s	1	1
length s	1	1

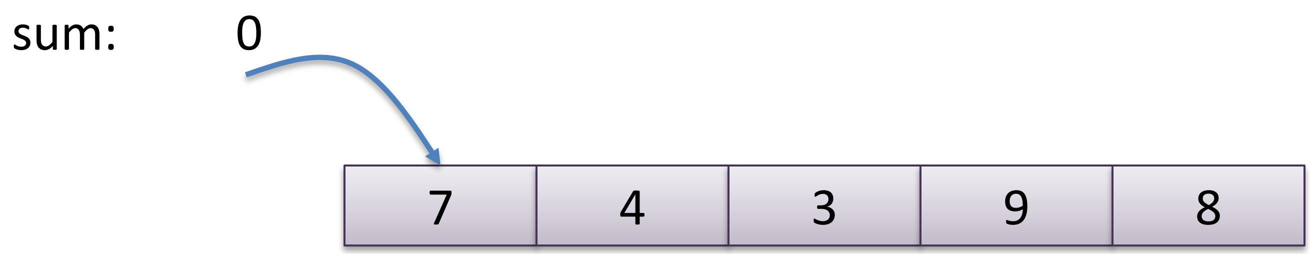
A Parallel Sequence API

	Work	Span
`type 'a seq`		
`tabulate : (int -> 'a) -> int -> 'a seq`	O(N)	O(1)
`length : 'a seq -> int`	O(1)	O(1)
`nth : 'a seq -> int -> 'a`	O(1)	O(1)
`append : 'a seq -> 'a seq -> 'a seq` (can build this from tabulate, nth, length)	O(N+M)	O(1)
`split : 'a seq -> int -> 'a seq * 'a seq`	O(N)	O(1)

For efficient implementations, see Blelloch's NESL project:
http://www.cs.cmu.edu/~scandal/nesl.html

Fold and Reduce

We have seen many sequential algorithms can be programmed succinctly using fold or reduce. Eg: sum all elements:



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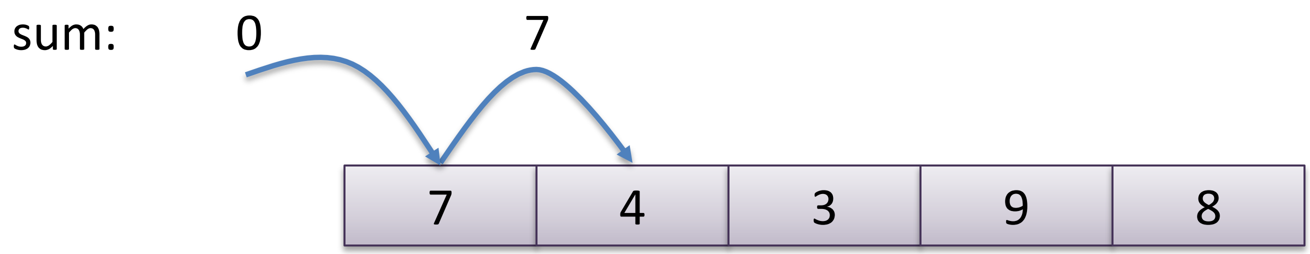

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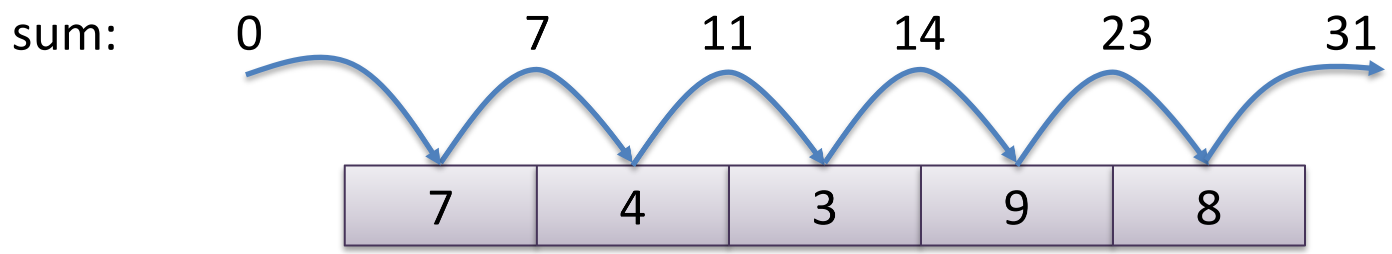

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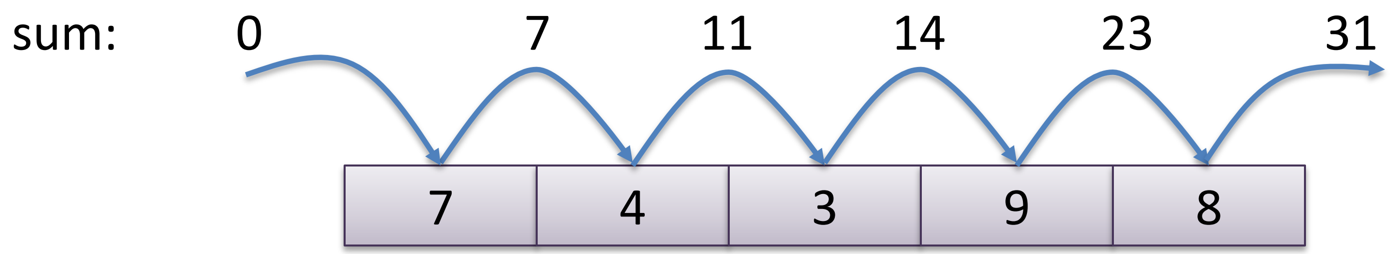


```
let sum_all (l:int list) = reduce (+) 0 l
```

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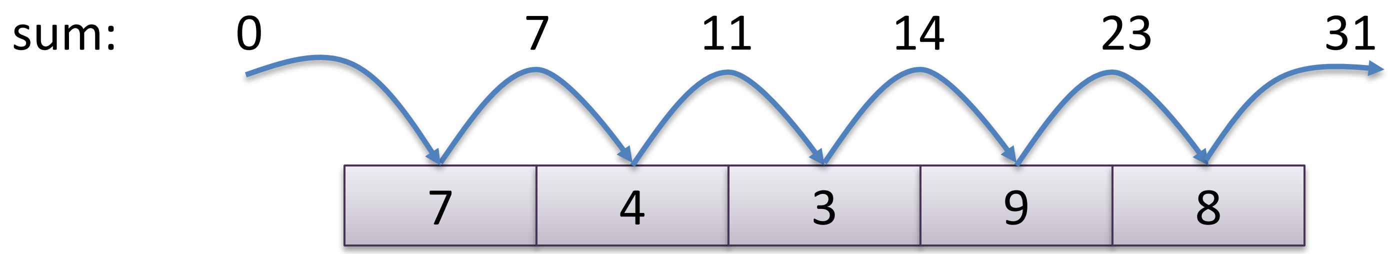



```
let sum_all (l:int list) = reduce (+) 0 l
```

Key to parallelization: Notice that because sum is an *associative* operator, we do not have to add the elements strictly left-to-right:

((((init + v1) + v2) + v3) + v4) + v5) == ((init + v1) + v2) + ((v3 + v4) + v5)

add on processor 1

add on processor 2

Side Note

The key is *associativity*:

(((((init + v1) + v2) + v3) + v4) + v5) == ((init + v1) + v2) + ((v3 + v4) + v5)

add on processor 1

add on processor 2

Commutativity not needed!

Commutativity allows us to reorder the elements:

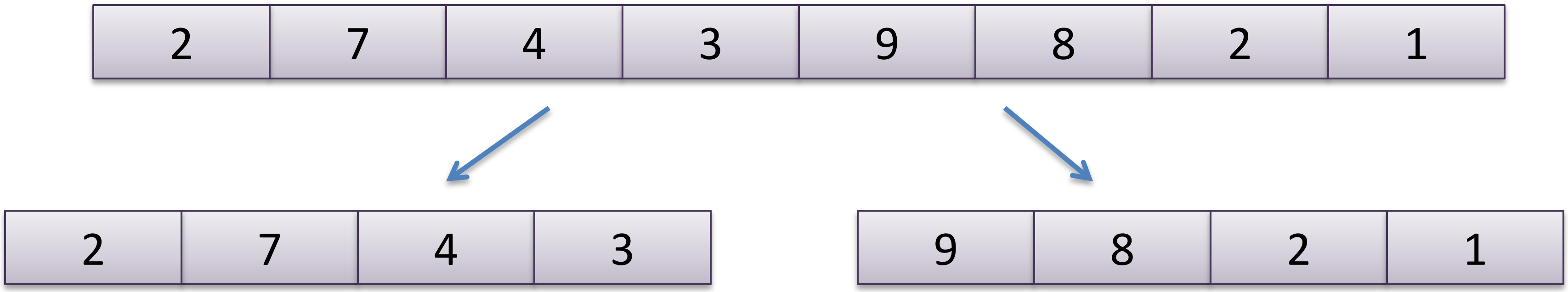
v1 + v2 == v2 + v1

But we don't have to reorder elements to obtain a significant speedup; we just have to reorder the execution of the operations.

Parallel Sum

2	7	4	3	9	8	2	1

Parallel Sum



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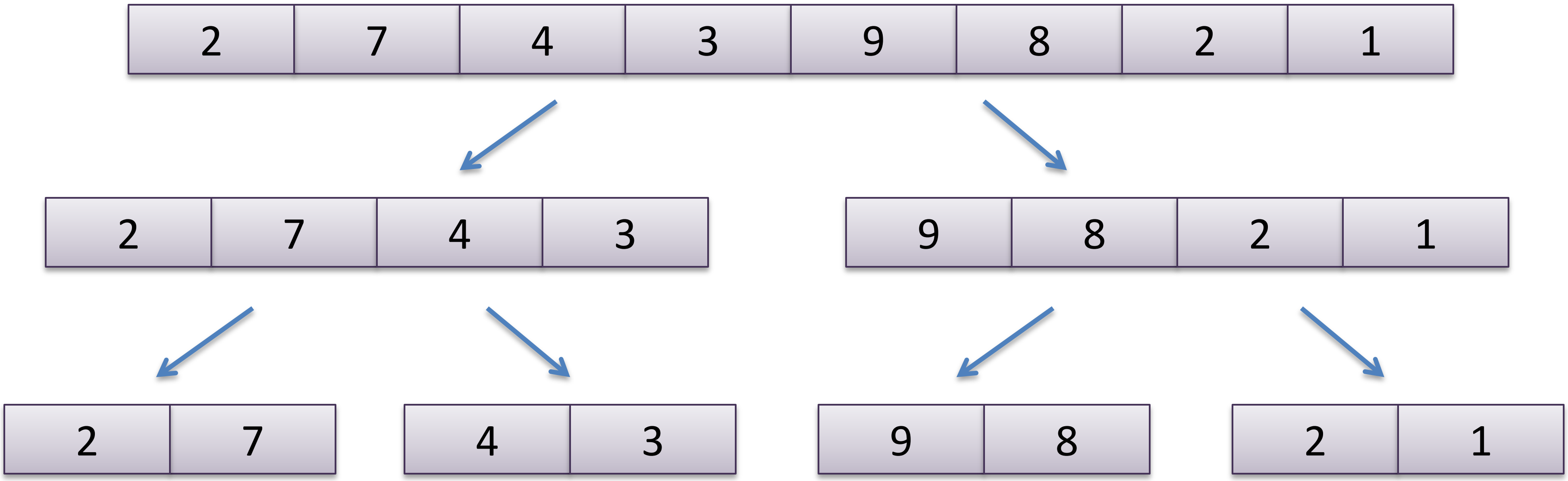

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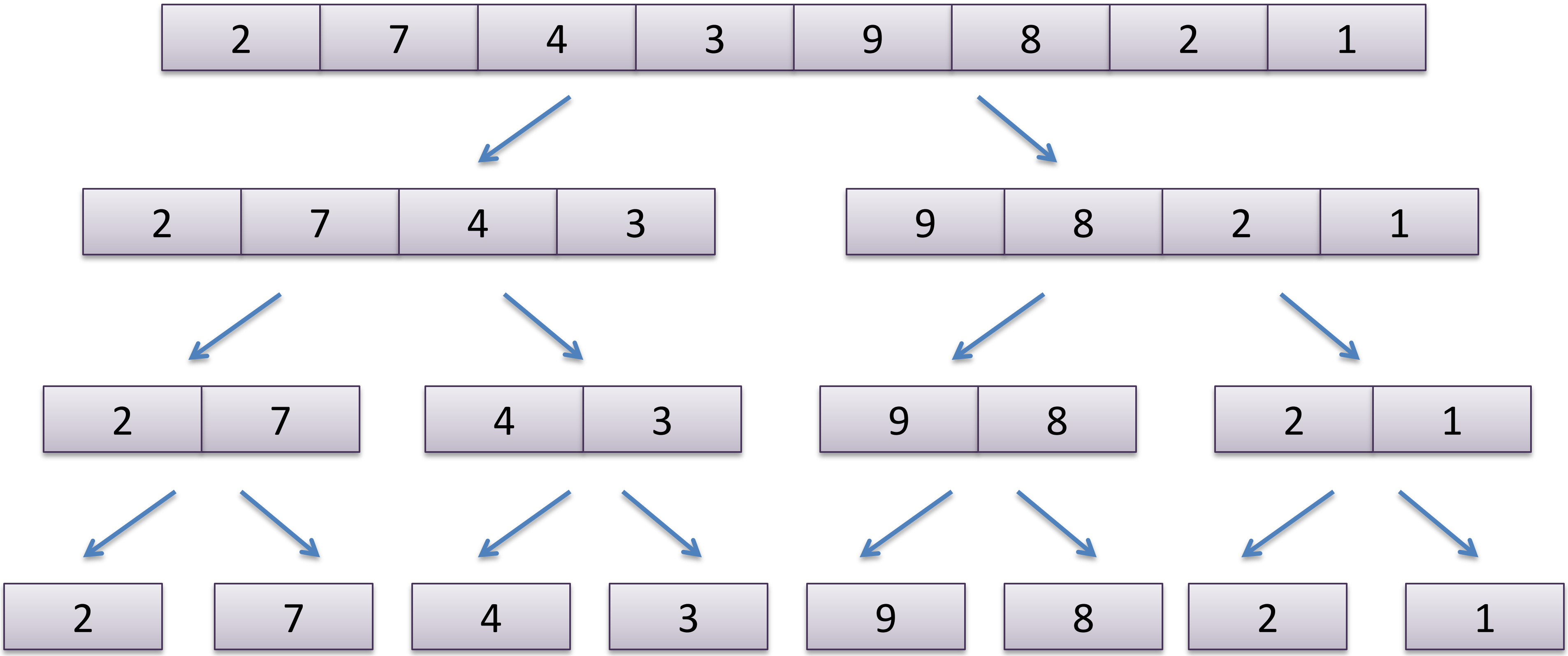

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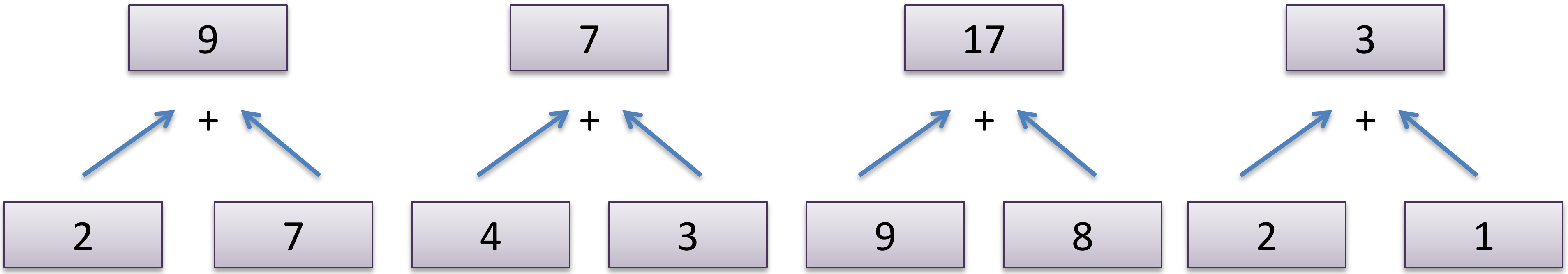

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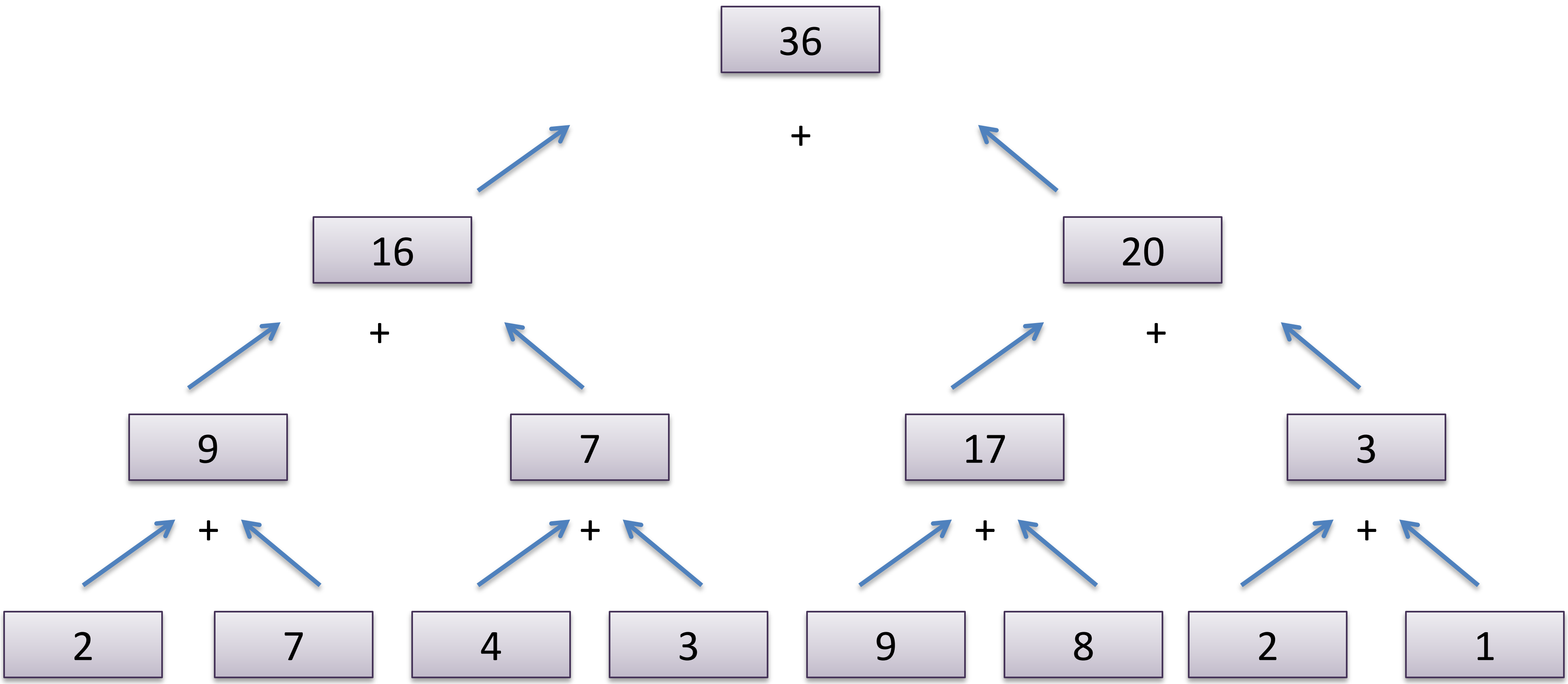
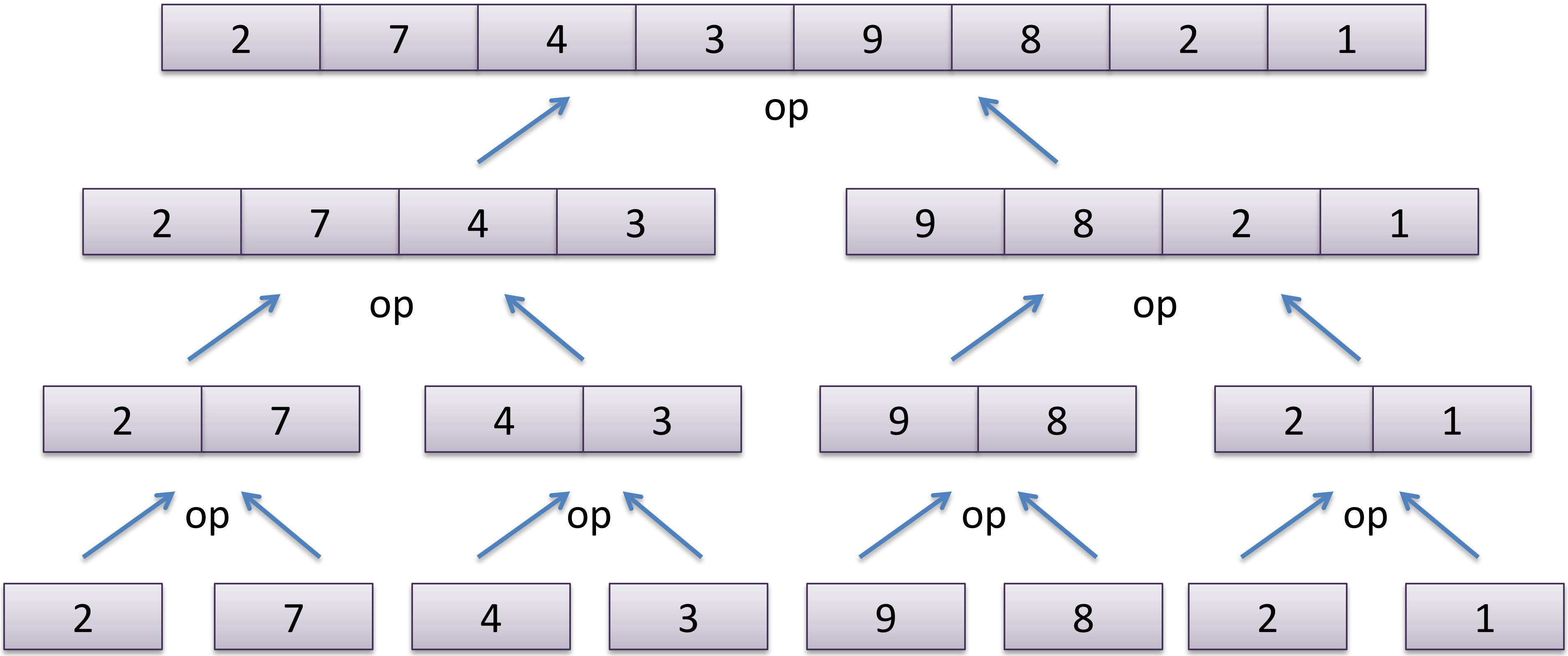


Parallel Sum

```
let both f x g y =
  let ff = future f x in
  let gv = g y in
  (force ff, gv)
```

```
let rec psum (s : int seq) : int =
  match length s with
    0 -> 0
  | 1 -> nth s 0
  | n ->
      let (s1,s2) = split (n/2) s in
      let (a1, a2) = both psum s1
                          psum s2 in
      a1 + a2
```

Parallel Reduce



If op is associative and the base case has the properties:

op base X == X op X base == X

then the parallel reduce is equivalent to the sequential left-to-right fold.

Parallel Reduce

```
let rec reduce (f:'a -> 'a -> 'a) (base:'a) (s:'a seq) =
  match length s with
    0 -> base
  | 1 -> nth s 0
  | n ->
      let (s1,s2) = split (n/2) s in
      let (n1, n2) = both (reduce f base) s1
                          (reduce f base) s2 in
      f n1 n2
```

Parallel Reduce

```
let rec reduce (f:'a -> 'a -> 'a) (base:'a) (s:'a seq) =
  match length s with
    0 -> base
  | 1 -> nth s 0
  | n ->
      let (s1,s2) = split (n/2) s in
      let (n1, n2) = both (reduce f base) s1
                          (reduce f base) s2 in
      f n1 n2
```

```
let sum s = reduce (+) 0 s
```

A little more general

```
let rec mapreduce (inject: 'a -> 'b)
                  (combine:'b -> 'b -> 'b)
                  (base:'b)
                  (s:'a seq) =
  match length s with
    0 -> base
  | 1 -> inject (nth s 0)
  | n ->
      let (s1,s2) = split (n/2) s in
      let (n1, n2) = both
                     (mapreduce inject combine base) s1
                     (mapreduce inject combine base) s2 in
      combine n1 n2
```

A little more general

```
let rec mapreduce (inject: 'a -> 'b)
                  (combine:'b -> 'b -> 'b)
                  (base:'b)
                  (s:'a seq) =
  match length s with
    0 -> base
  | 1 -> inject (nth s 0)
  | n ->
      let (s1,s2) = split (n/2) s in
      let (n1, n2) = both
                     (mapreduce inject combine base) s1
                     (mapreduce inject combine base) s2 in
      combine n1 n2
```

```
let average s =
  let (count, total) =
    mapreduce (fun x -> (1,x))
              (fun (c1,t1) (c2,t2) -> (c1+c2, t1 + t2))
              (0,0) s in
  if count = 0 then 0 else total / count
```

DON’T PARALLELIZE AT TOO FINE A GRAIN

Parallel Reduce with Sequential Cut-off

When data is small, the overhead of parallelization isn't worth it.
Revert to the sequential version!

```
let sequential_reduce f base (s:'a seq) =
   let rec g i x =
       if i<0 then x else g (i-1) (f (nth a i) x)
    in g (length s - 1)
```

```
let SHORT = 1000

let rec reduce (f:'a -> 'a -> 'a) (base:'a) (s:'a seq) =
  if length s < SHORT
  then sequential_reduce f base s
  else let (s1,s2) = split ((length s)/2) s in
       let (n1, n2) = both (reduce f base) s1
                           (reduce f base) s2 in
       f n1 n2
```