Eden: Parallel Processes, Patterns and Skeletons

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Learning Goals:

- Writing programs in the parallel Haskell dialect Eden
- Reasoning about the behaviour of Eden programs.
- Applying and implementing parallel skeletons in Eden

Eden Constructs in a Nutshell

- Developed since 1996 in Marburg and Madrid
- Haskell, extended by communicating processes for coordination

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Eden constructs for Process abstraction and instantiation

```
process ::(Trans a, Trans b)=> (a -> b) -> Process a b
( # ) :: (Trans a, Trans b) => (Process a b) -> a -> b
spawn :: (Trans a, Trans b) => [ Process a b ] -> [a] -> [b]
```

- Distributed Memory (Processes do not share data)
- Data sent through (hidden) 1:1 channels
- Type class `Trans`:
  - stream communication for lists
  - concurrent evaluation of tuple components
- Full evaluation of process output (if any result demanded)
- Non-functional features: explicit communication, $n : 1$ channels

Quick Sidestep: WHNF, NFData and Evaluation

- Weak Head Normal Form (WHNF):
  Evaluation up to the top level constructor

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- Weak Head Normal Form (WHNF):
  Evaluation up to the top level constructor

- Normal Form (NF):
  Full evaluation (recursively in sub-structures)

From *Control.DeepSeq*

```
class NFData a where
    rnf :: a -> ()          -- This was a _Strategy_ in 1998
    rnf a = a `seq` ()      -- returning unit ()

instance NFData Int
instance NFData Double
...
instance (NFData a) => NFData [a] where
    rnf [] = ()
    rnf (x:xs) = rnf x `seq` rnf xs
...
instance (NFData a, NFData b) => NFData (a,b) where
    rnf (a,b) = rnf a `seq` rnf b
```

Essential Eden: Process Abstraction/Instantiation

Process **Abstraction**: `process ::... (a -> b) -> Process a b`

```
multproc = process (\x -> [ x*k | k <- [1,2..]])
```

Essential Eden: Process Abstraction/Instantiation

Process Abstraction: `process ::... (a -> b) -> Process a b`

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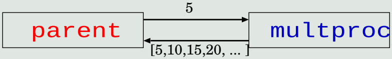
multproc = process (\x -> [ x*k | k <- [1,2..]])
```

Process Instantiation: `(#) ::... Process a b -> a -> b`

```
multiple5 = multproc # 5
```



- Full evaluation of argument (concurrent) and result (parallel)
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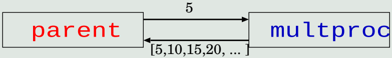
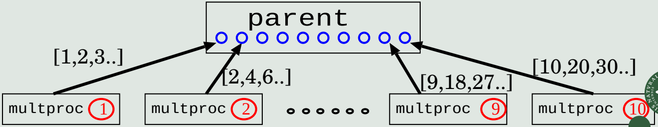


- Full evaluation of argument (concurrent) and result (parallel)
- Stream communication for lists

Spawning **multiple processes**: `spawn ::... [Process a b] -> [a] -> [b]`

```
multiples = spawn (replicate 10 multproc) [1..10]
```



A Small Eden Example[1]

- Subexpressions evaluated in parallel
- ... in different processes with separate heaps

simpleeden.hs

```
main = do args <- getArgs
          let first_stuff = (process f_expensive) # (args!!0)
              other_stuff = g_expensive $# (args!!1) -- syntax variant
          putStrLn (show first_stuff ++ '\n':show other_stuff)
```

[1](compiled with option -parcp or -parmpi)

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...which will not produce any speedup!

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          putStrLn (show first_stuff ++ '\n':show other_stuff)
```

... which will not produce any speedup!

simpleeden2.hs

```
main = do args <- getArgs
          let [first_stuff,other_stuff]
                    = spawnF [f_expensive, g_expensive] args
          putStrLn (show first_stuff ++ '\n':show other_stuff)
```

- Processes are created when there is demand for the result!
- Spawn both processes at the same time using special function.

[1](compiled with option -parcp or -parmpi)

Basic Eden Exercise: Hamming Numbers

The Hamming Numbers are defined as the ascending sequence of numbers:

$$\left\{ 2^i \cdot 3^j \cdot 5^k \mid i, j, k \in \mathbb{N} \right\}$$

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Dijkstra:

The first Hammng number is 1. Each following Hamming number H can be written as $H = 2K$, $H = 3K$, or $H = 5K$; with a suitable smaller Hamming number K.

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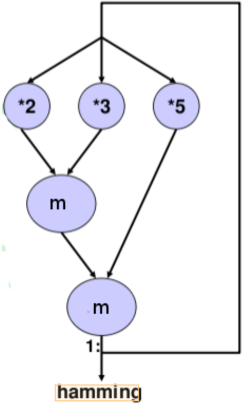
Dijkstra:
The first Hammng number is 1. Each following Hamming number H can be written as $H = 2K$, $H = 3K$, or $H = 5K$; with a suitable smaller Hamming number K.

- Write an Eden program that produces Hamming numbers using parallel processes. The program should take one argument n and produce the numbers up to position n.
- Observe the parallel behaviour of your program using EdenTV.



Non-Functional Eden Constructs for Optimisation

Location-Awareness: `noPe, selfPe :: Int`

```
spawnAt :: (Trans a, Trans b) => [Int] -> [Process a b] -> [a] -> [b]
instantiateAt :: (Trans a, Trans b) =>
                 Int -> Process a b -> a -> IO b
```

Non-Functional Eden Constructs for Optimisation

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Explicit communication using primitive operations (monadic)

```
data ChanName = Comm (Channel a -> a -> IO ())
createC :: IO (Channel a , a)

class NFData a => Trans a where
    write :: a -> IO ()
    write x = rdeepseq x `pseq` sendData Data x
    createComm :: IO (ChanName a, a)
    createComm = do (cx,x) <- createC
                    return (Comm (sendVia cx) , x)
```

Nondeterminism! `merge :: [[a]] -> [a]`

Hidden inside a Haskell module, only for the library implementation.

Outline

The Idea of Skeleton-Basked Parallelism

You have already seen one example:

- Divide and Conquer, as a higher-order function

```
divConqB :: (a -> b) -> a     -- base case fct., input
         -> (a -> Bool)       -- parallel threshold
         -> (b -> b -> b)     -- combine
         -> (a -> Maybe (a,a)) -- divide
         -> b
divConqB baseF input doSeq combine divide = ...
```

  (type will be modified later)

- Parallel structure (binary tree) exploited for parallelism
- Abstracted from concrete problem

The Idea of Skeleton-Basked Parallelism

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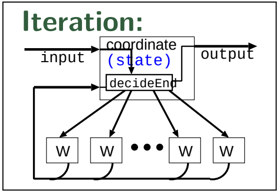
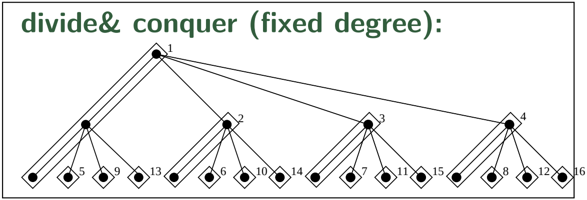
And another one, much simpler, much more common:

```
parMap ::  (a->b) -> [a] -> [b]
```

Algorithmic Skeletons for Parallel Programming



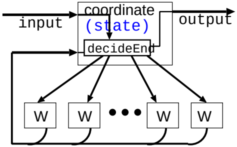


Algorithmic Skeletons [Cole 1989]: Boxes and lines – executable!

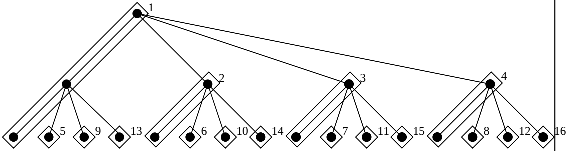
- Abstraction of algorithmic structure as a higher-order function

Algorithmic Skeletons for Parallel Programming

Iteration:



divide& conquer (fixed degree):



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- Abstraction of algorithmic structure as a higher-order function
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- Hidden parallel library implementation (by system programmer)

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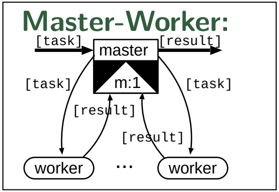

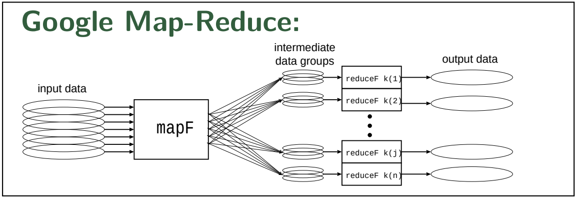

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- Abstraction of algorithmic structure as a higher-order function
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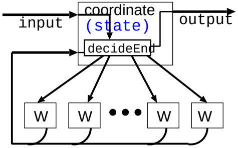

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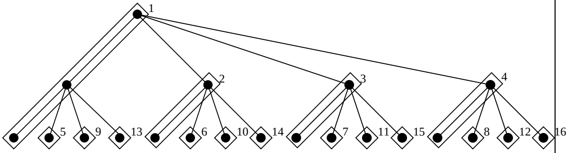

Algorithmic Skeletons [Cole 1989]: Boxes and lines – executable!

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- Hidden parallel library implementation (by system programmer)
- Different kinds of skeletons: topological, small-scale, algorithmic

Explicit parallelism control and functional paradigm are a good setting to implement and use skeletons for parallel programming.

Types of Skeletons

Common Small-scale Skeletons

- encapsulate common parallelisable operations or patterns
- parallel behaviour (concrete parallelisation) hidden

Structure-oriented: Topology Skeletons

- describe interaction between execution units
- explicitly model parallelism

Proper Algorithmic Skeletons

- capture a more complex algorithm-specific structure
- sometimes domain-specific

Outline

Basic Skeletons: Higher-Order Functions

- Parallel transformation: Map

```
map :: (a -> b) -> [a] -> [b]
```

independent elementwise transformation

... probably the most common example of parallel functional programming (called "embarassingly parallel")

Basic Skeletons: Higher-Order Functions

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independent elementwise transformation

…probably the most common example of parallel functional programming (called "embarassingly parallel")

- Parallel Reduction: Fold

```
fold :: (a -> a -> a) -> [a] -> a
```

with commutative and associative operation.

- Parallel Scan:

```
parScanL :: (a -> a -> a) -> [a] -> [a]
```

reduction keeping the intermediate results.

- Parallel Map-Reduce:

combining transformation and groupwise reduction.

Embarassingly Parallel: `map`

`map`: apply transformation to all elements of a list

- Straight-forward element-wise parallelisation

```
parmap :: (Trans a, Trans b) => (a -> b) -> [a] -> [b]
parmap  = spawn . repeat . process
     -- parmap f xs = spawn (repeat (process f)) xs
```

Embarassingly Parallel: map

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```

Much too fine-grained!

- Group-wise processing: Farm of processes

```
farm :: (Trans a, Trans b) => (a -> b) -> [a] -> [b]
farm f xs = join results
    where results = spawn (repeat (process (map f))) parts
          parts   = distribute noPe xs -- noPe, so use all nodes
          join    = ...
          distribute n = ... -- join . distribute n == id
```

Example

Mandelbrot set visualisation $z_{n+1} = z_n^2 + c$ for $c \in \mathbb{C}$

Mandelbrot (Pseudocode)

```
pic :: ..picture-parameters.. -> PPMAscii
pic threshold ul lr dimx np s = ppmheader ++ concat (parMap computeRow rows)
   where rows = ...dimx..ul..lr..
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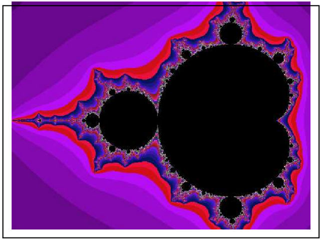
```



Example / Exercise

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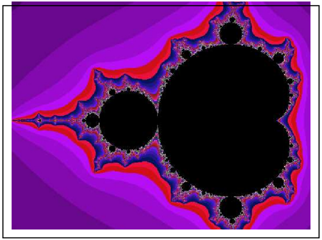

Exercise:

- Implement parMap in 2 different ways
- Run the Mandelbrot program with both versions, compare the behaviour.

Framework programs can be found on the course pages. . .

Example / Exercise: Chunked Tasks

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Mandelbrot (Pseudocode)

```
pic :: ..picture-parameters.. -> PPMAscii
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   where rows = ...dimx..ul..lr..
         parMap = ..using chunks..
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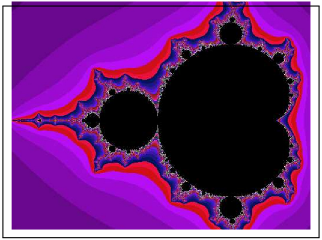

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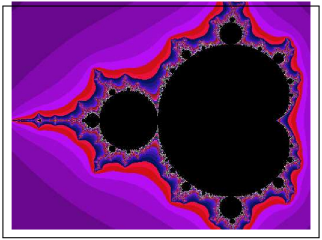
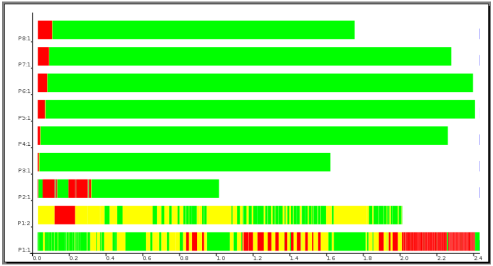




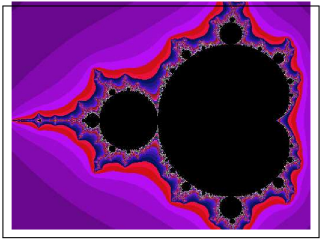
Simple chunking leads to load imbalance (task complexities differ)

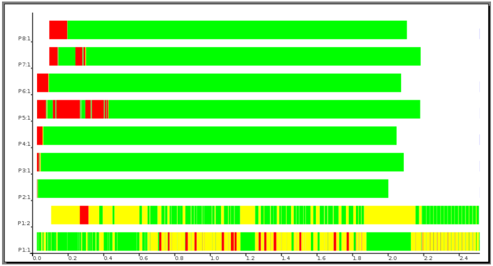
Example / Exercise: Round-robin Tasks

Mandelbrot set visualisation $z_{n+1} = z_n^2 + c$ for $c \in \mathbb{C}$

Mandelbrot (Pseudocode)

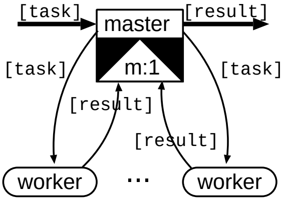
```
pic :: ..picture-parameters.. -> PPMAscii
pic threshold ul lr dimx np s = ppmheader ++ concat (parMap computeRow rows)
   where rows = ...dimx..ul..lr..
         parMap = ..distributing round-robin..
```





Better: round-robin distribution, but still not well-balanced.

Master-Worker Skeleton



Worker nodes transform elementwise:

```
worker ::  task -> result
```

Master node manages task pool

```
mw  :: Int -> Int ->
       ( a -> b ) -> [a] -> [b]
mw np prefetch f tasks =  ...
```

Parameters: no. of workers, prefetch

- Master sends a new task each time a result is returned (needs many-to-one communication)
- Initial workload of `prefetch` tasks for each worker:
  Higher prefetch ⇒ more and more static task distribution
  Lower prefetch ⇒ dynamic load balance

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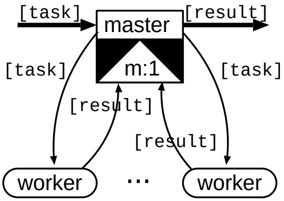

Parameters: no. of workers, prefetch

- Master sends a new task each time a result is returned (needs many-to-one communication)
- Initial workload of `prefetch` tasks for each worker:
  Higher prefetch ⇒ more and more static task distribution
  Lower prefetch ⇒ dynamic load balance
- Result order needs to be reestablished!

Master-Worker: An Implementation

Master-Worker Skeleton Code

```
mw np prefetch f tasks = results
 where
  fromWorkers          = spawn workerProcs toWorkers
  workerProcs          = [process (zip [n,n..] . map f) | n<-[1..np]]
  toWorkers            = distribute tasks requests
```

- Workers tag results with their ID (between 1 and `np`).

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 where
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  (newReqs, results) = (unzip . merge) fromWorkers
  requests             = initialReqs ++ newReqs
  initialReqs          = concat (replicate prefetch [1..np])
```

- Workers tag results with their ID (between 1 and `np`).
- Result streams are non-deterministically merged into one stream.

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Master-Worker Skeleton Code

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  (newReqs, results) = (unzip . merge) fromWorkers
  requests             = initialReqs ++ newReqs
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  distribute :: [t] -> [Int] -> [[t]]
  distribute tasks reqs = [taskList reqs tasks n | n<-[1..np]]
     where taskList (r:rs) (t:ts) pe | pe == r     = t:(taskList rs ts pe)
                                     | otherwise   =    taskList rs ts pe
           taskList _      _      _  = []
```

- Workers tag results with their ID (between 1 and `np`).
- Result streams are non-deterministically merged into one stream.
- The `distribute` function supplies new tasks according to requests.

Parallel Reduction, Map-Reduce

Reduction (`fold`) usually has a direction

- ```
  foldl :: (b -> a -> b) -> b -> [a] -> b
  foldr :: (a -> b -> b) -> b -> [a] -> b
  ```

  Starting from the left or right, implying different reduction function.
- To parallelise: break into sublists and pre-reduce in parallel.
- Better options if order does not matter.
  ```

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- To parallelise: break into sublists and pre-reduce in parallel.
- Better options if order does not matter.

Example: $\sum_{k=1}^{n} \varphi(k) = \sum_{k=1}^{n} |\{j < k \mid gcd(k,j) = 1\}|$ (Euler Phi)

sumEuler

```
result = foldl (+) 0 (map phi [1..n])
phi k = length (filter (\ n -> gcd n k == 1) [1..(k-1)])
```
```

Parallel Map-Reduce: Restrictions

- ```
  parmapReduceStream :: Int ->
                        (a -> b) -> (b -> b -> b) -> b ->
                        [a] -> b
  parmapReduceStream np mapF redF neutral list = foldl redF neutral subRs
      where sublists = distribute np list
            subFold  = process (foldl' redF neutral . (map mapF))
            subRs    = spawn (replicate np subFold) sublists
  ```
  ```

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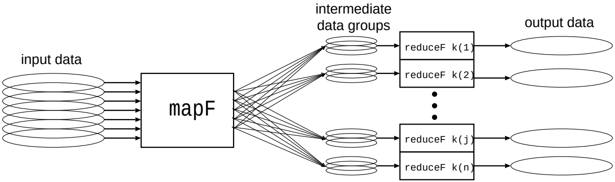
  ```
- Associativity and neutral element (essential).
- commutativity (desired, more liberal distribution)
- need to narrow type of the reduce parameter function!
- ... Alternative `fold` type:
  ```
  redF' :: [b] -> b
  redF'    []    = neutral
  redF' (x:xs) = foldl' redF x xs
  ```
  ```

Google Map-Reduce: Grouping Before Reduction

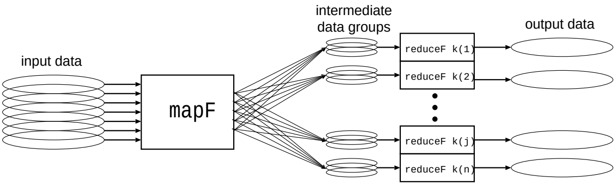
```
gMapRed :: (k1 -> v1 -> [(k2,v2)])       -- mapF
           -> (k2 -> [v2] -> Maybe v3) -- reduceF
           -> Map k1 v1 -> Map k2 v3   -- input / output
```



1. Input: key-value pairs `(k1,v1)`, many or no outputs `(k2,v2)`
2. Intermediate grouping by key `k2`
3. Reduction per (intermediate) key `k2` (maybe without result)
4. Input and output: Finite mappings

Google Map-Reduce: Grouping Before Reduction

```
gMapRed :: (k1 -> v1 -> [(k2,v2)])      -- mapF
        -> (k2 -> [v2] -> Maybe v3)  -- reduceF
        -> Map k1 v1 -> Map k2 v3     -- input / output
```

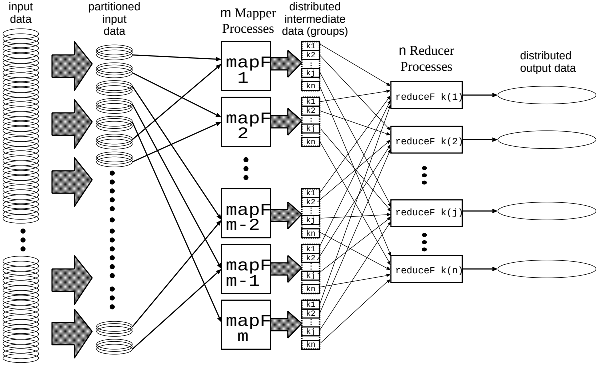



```
Document      ->      [(word,1)]      ->      word,count
```

Word Occurrence

```
mapF :: URL -> String -> [(String,Int)]
mapF _ content = [(word,1) | word <- words content ]
reduceF :: String -> [Int] -> Maybe Int
reduceF word counts = Just (sum counts)
```

Google Map-Reduce (parallel)



R.Lämmel, Google's Map-Reduce Programming Model Revisited. In: SCP 2008

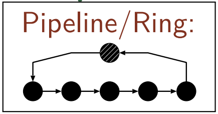
```
gMapRed :: Int -> (k2->Int) -> Int -> (v1->Int) -- parameters
           (k1 -> v1 -> [(k2,v2)])       -- mapper
           -> (k2 -> [v2] -> Maybe v3) -- pre-reducer
           -> (k2 -> [v3] -> Maybe v4) -- final reducer
           -> Map k1 v1 -> Map k2 v4   -- input / output
```

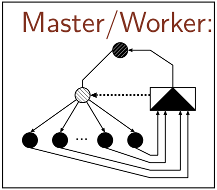
Outline

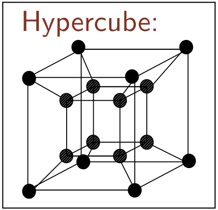
Process Topologies as Skeletons: Explicit Parallelism

- describe typical patterns of parallel interaction structure
- (where node behaviour is the function argument)
- to structure parallel computations

Examples:







Process Topologies as Skeletons: Explicit Parallelism

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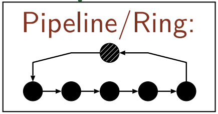
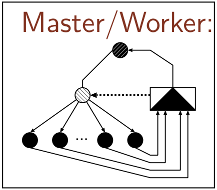
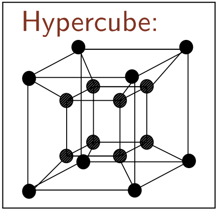
Examples:

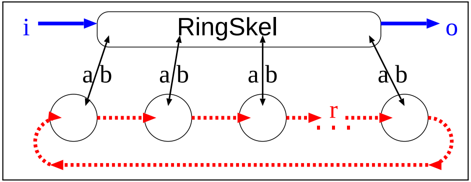






⇒ well-suited for functional languages (with explicit parallelism).
Skeletons can be implemented and applied in Eden.

Process Topologies as Skeletons: Ring




```
type RingSkel i o a b r = Int -> (Int -> i -> [a]) -> ([b] -> o) ->
                           ((a,[r]) -> (b,[r])) -> i -> o

ring size makeInput processOutput ringWorker input = ...
```

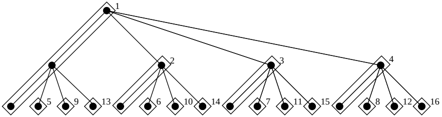
- Good for exchanging (updated) global data between nodes
- All ring processes connect to parent to receive input/send output
- Parameters: functions for
  - decomposing input, combining output, ring worker

Outline

Two Algorithm-oriented Skeletons

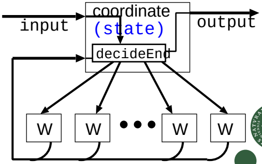
- Divide and conquer

```
divCon :: (a -> Bool) -> (a -> b)      -- trivial? / then solve
          -> (a -> [a]) -> ([b] -> b) -- split / combine
          -> a -> b                    -- input / result
```



- Iteration

```
iterateUntil :: (inp -> ([ws],[t],ms)) ->           -- split/init function
                (t -> State ws r) ->                -- worker function
                ([r] -> State ms (Either out [t])) -- manager function
                -> inp -> out
```



Divide and Conquer Skeletons

- General version: no assumptions on problem characteristics

```
divCon :: (a -> Bool) -> (a -> b)      -- trivial? / then solve
          -> (a -> [a]) -> ([b] -> b) -- split / combine
          -> a -> b                   -- input / result
divCon trivial solve split combine = ...
```

- Implementation will make (parallel?) recursive calls to itself (with same parameters as the initial call).

Divide and Conquer Skeletons

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          -> a -> b                   -- input / result
divCon trivial solve split combine = ... -- you write one
```

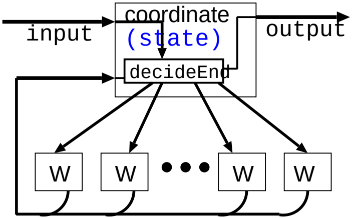
- Implementation will make (parallel?) recursive calls to itself (with same parameters as the initial call).

Exercise:

- Implement this general divide-and-conquer version.
  Write a sequential version first, then make recursive calls parallel.
  Add one `Int` parameter to limit the parallel depth.

Iteration Skeleton

- Fixed set of workers
- Lock-step execution, solving a set of tasks
- Manager decides end

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                ([r] -> State ms (Either out [t])) -- manager function
                -> inp -> out
```

Worker: computes result `r` from task `t`
using and updating a local state `ws`

Manager: decides whether to continue,
based on master state `ms` and all worker results.
produce tasks for all workers

Outline

Summary

- Eden: Explicit parallel processes, mostly functional face
- Two levels of Eden: Skeleton implementation and skeleton use
  - Skeletons: High-level specification exposes parallel structure
  - and enables programmers to think in parallel patterns.
- Different skeleton categories (increasing abstraction)
  - Small-scale skeletons (map, fold, map-reduce, ...)
  - Process topology skeletons (ring, ...)
  - Algorithmic skeletons (divide & conquer, iteration)

Summary

- Eden: Explicit parallel processes, mostly functional face
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  - Process topology skeletons (ring, . . .)
  - Algorithmic skeletons (divide & conquer, iteration)
- More information on Eden:

`http://www.mathematik.uni-marburg.de/~eden`

(`http://hackage.haskell.org/package/edenskel/`)

(`http://hackage.haskell.org/package/edenmodules/`)

Exercises for the Lab

1. Complete the Hamming number program
   File: `hamming-.hs`
   Execute the program and look at an execution trace using EdenTV
2. Implement two versions of parMap which increase granularity
   Files: `ParMap.hs`, `mandel.hs`
   Test your versions using the Mandelbrot program.
3. Implement the Divide-And-Conquer skeleton
   Files: `DC.hs`, `mergesort.hs`
   Test your skeleton implementation using the provided mergesort program.
4. (Bonus) Implement a simple quicksort program using the skeleton

Usage example:

Compile example, (with tracing -eventlog):

```
berthold@bwlf01$ COMPILER  -parcp -eventlog -O2 -rtsopts --make mandel.hs
[1 of 2] Compiling ParMap           ( ParMap.hs, ParMap.o )
[2 of 2] Compiling Main             ( mandel.hs, mandel.o )
Linking mandel ...
```

Run, second run with tracing:

```
berthold@bwlf01$  ./mandel 0 200 1 -out +RTS -qp4  > out.ppm
==== Starting parallel execution on 4 processors ...
berthold@bwlf01$ ./mandel 0 50 1 +RTS -qp4 -l
==== Starting parallel execution on 4 processors ...
Done (no output)
Trace post-processing...
  adding: berthold=mandel#1.eventlog (deflated 65%)
  adding: berthold=mandel#2.eventlog (deflated 59%)
  adding: berthold=mandel#3.eventlog (deflated 58%)
  adding: berthold=mandel#4.eventlog (deflated 58%)
berthold@bwlf01$ edentv berthold\=mandel_0_50_1_+RTS_-qp4_-l.parevents
```