TDDD56: Multicore and GPU programming
Lesson 1
Introduction to laboratory work

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Today

Lab 1: Load balancing

- Parallelize the generation of the graphic representation of a subset of Mandelbrot set.

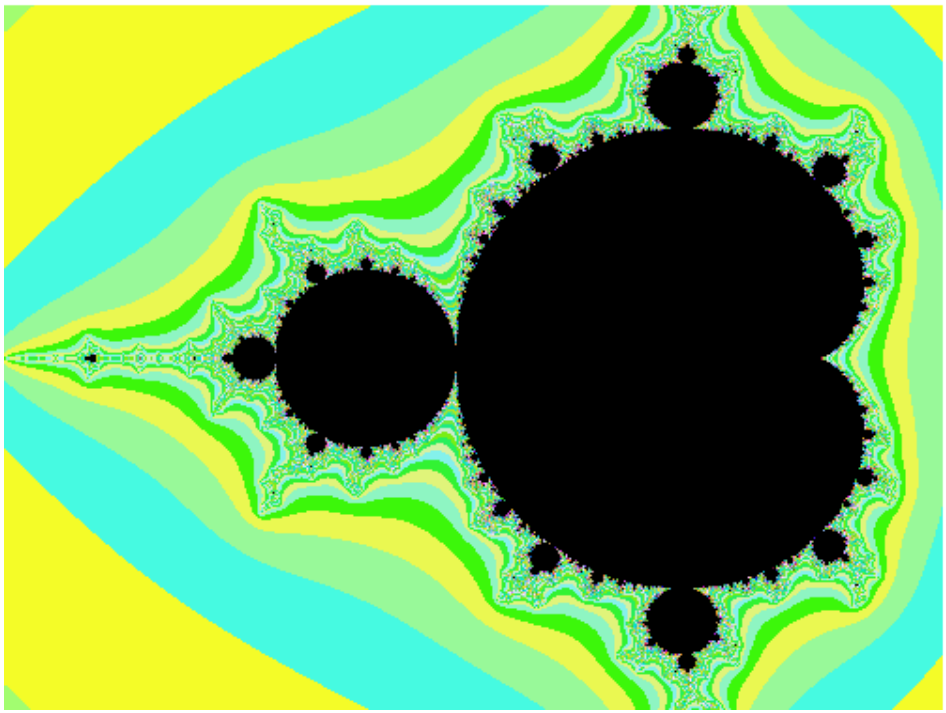


Figure: A representation of the Mandelbrot set (black area) in the range $-2 \leq C^{re} \leq 0.6$ and $-1 \leq C^{im} \leq 1$.

Computing 2D representation of the Mandelbrot set

- Let $P = \{(a, b \cdot i) : a \in [C^{re}_{min}, C^{re}_{max}] \wedge b \in [C^{im}_{min}, C^{im}_{max}]\} \subset \mathbb{C}$.
- Represent P in a 2D picture of size $H \times W$ pixels.
- For each $p \in P$, we have exactly one pixel $(x, y) = (\frac{a \cdot H}{C^{re}_{max} - C^{re}_{min}}, \frac{b \cdot W}{C^{im}_{max} - C^{im}_{min}})$ in the picture
- $p \in M$ iif the Julia sequence (eq. 1) is bound to $b \in \mathbb{R}$ with $b > 0$ for $c = p$ starting at $z = (0, 0i)$.

$$\begin{cases} a_0 & = z \\ a_{n+1} & = a_n^2 + c, \forall n \in \{\forall x \in \mathbb{N} : n \neq 0\} \end{cases} \quad (1)$$

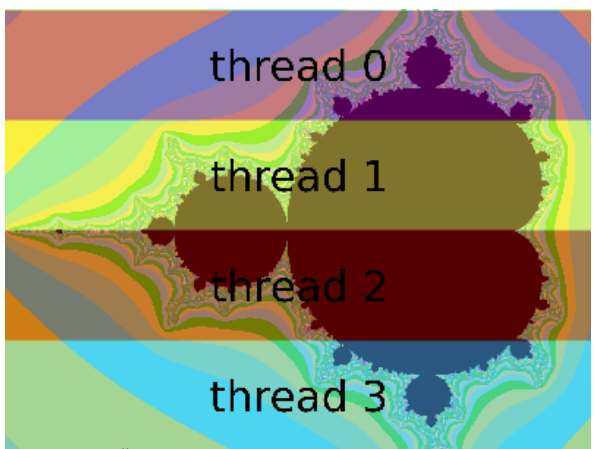
- Iterative algorithm implemented and provided

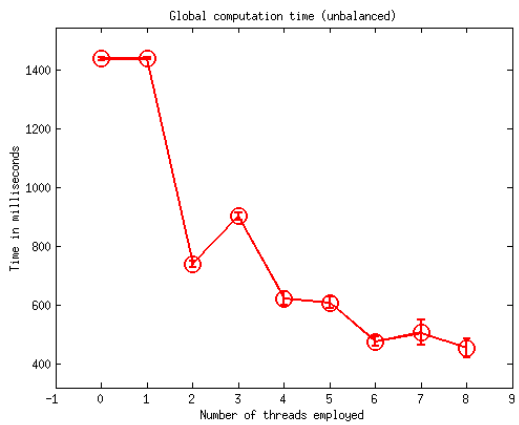
Computing 2D representation of the Mandelbrot set

```
int is_in_Mandelbrot(float Cre, float Cim) {
    int iter;
    float x=0.0, y=0.0, xto2=0.0, yto2=0.0, dist2;
    for (iter = 0; iter <= MAXITER; iter++) {
        y = x * y;
        y = y + y + Cim;
        x = xto2 – yto2 + Cre;
        xto2 = x * x;
        yto2 = y * y;
        dist2 = xto2 + yto2;
        if ((int) dist2 >= MAXDIV) {
            break; // diverges
        } }
    return iter;
}
```

Computing 2D representation of the Mandelbrot set

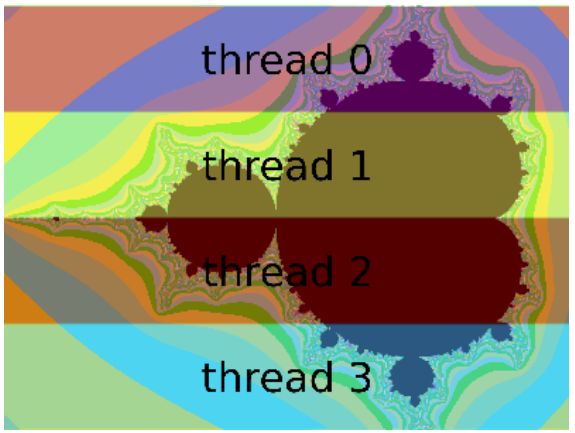
- *is_in_mandelbrot*(C^{re}, iC^{im}) returns n
  - If $n >= MAXITER$ then the pixel is black
  - Otherwise the pixel takes the n^{th} color of a *MAXITER* color gradient.
- Take each pixel (h, w), run *is_in_mandelbrot*(h, w) and deduce a suitable color
- Data-parallel, “embarassingly parallel”
- Load-balancing issues

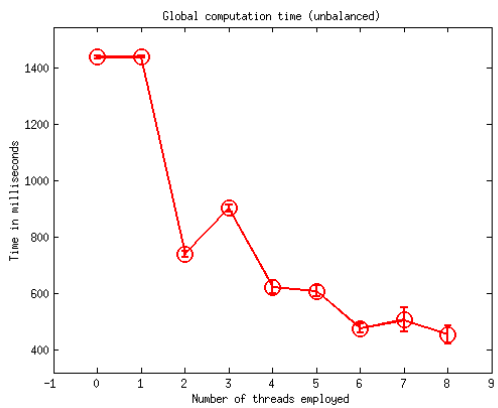




Lab 1: Load balancing

- A sequential code is provided
- Parallelize it using threads and pthread library.
  - Naive: partition work as upper right figure. Performance like lower right figure
  - Load-balanced: performance scale with number of threads.
    - Independant from *P* to compute
  - Measure individual threads' execution time. Compare global naive and balanced execution time.
- Hints in necessary modifications:
  - *mandelbrot.c*: modify from line 122 to 146
  - You may modify anything else if you want
- More details and hints in lab compendium (read it!)





Lab 2: Non blocking data structures

- Synchronization of stacks
- Stack: LIFO (Last In, First Out) data structure with *push* and *pop* operations
  - Often a single linked list
  - *head* points to the head element
  - Empty if *head* $\rightarrow$ *null*

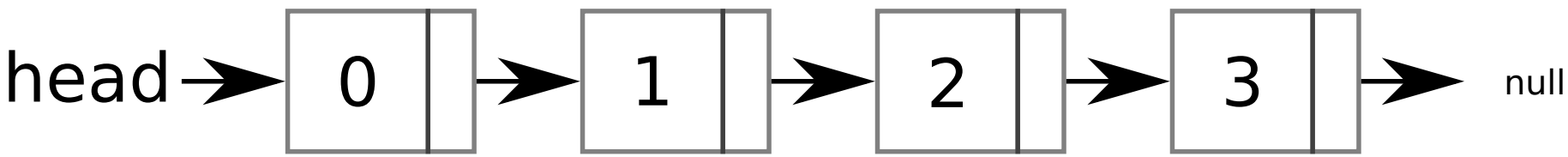


Figure: Unbounded stack

Stack synchronization

- Protects the stack during *push* or *pop* operations
- Atomically update head pointer
- Protection usually achieved thanks to a lock.

```
P(lock);
new_element.next = head;
head = &new_element;
V(lock);
```

Figure: Stack lock-based synchronization

Compare-and-swap

- Do atomically:
  - If *pointer* $\neq$ *old pointer* then return false
  - Else swap *pointer* to *new pointer* and return true

```
CAS(void** buf, void* old, void* new) {
   atomic {
      if(*buf = old) {
         *buf = new;
      }
   }
   return old;
}
```

- How to protect a stack with it?

CAS-protected stack

- Keep track to old head
- Set new element's *next* member to current head saved to old
- Check if head is still the one recorded in old
  - If so, commit the change
  - Else, restart the process (keep track, update new, check) until commit

```
do {
   old = head;
   elem.next = old;
} while(CAS(head, old, elem) != old);
```

Figure: CAS-protected push

CAS-protected stack

- If another thread preempts and push an element
  - Head is changed
  - CAS will fail
  - First thread tries again
- Thread 1 gets preempted by thread 2

```
   do {
      old = head;
      elem1.next = old;
<thread 2 preempts thread 1>
   } while(CAS(head, old, elem1) != old);

<just preempted thread 1>
   {
      old = head;
      elem2.next = old;
   } while(CAS(head, old, elem2) != old);
<returns to thread 1>
```

Misuses case of CAS

Why is the code below wrong...

```
push(stack_t stack, elem_t elem) {
   do {
      elem.next = head;
      old = head;
   } while(CAS(head, old, elem) != old);
}
```

... while this one is correct?

```
   do {
      old = head;
      elem.next = old;
   } while(CAS(head, old, elem) != old);
```

Treiber stack

- Rather old: published by R. Kent Treiber from IBM research in 1986.
  - Search “Coping with parallelism” on http://domino.research.ibm.com/library/cyberdig.nsf/index.html
- Relies on hardware CAS to atomically update the head of a stack to a new element.
- Pseudo code available on page 6 of “Nonblocking Algorithms and Preemption-Safe Locking on Multiprogrammed Shared Memory Multiprocessors” (M.M. Michael, M.L. Scott, *Journal of parallel and distributed computing*, 1998), available through google scholar.

The ABA problem

- Consider an unbounded stack
- Consider the element *pop*'ed elements are not destroyed, but pushed in a pool to be reused in further *push*()
  - Save a *malloc* to allocate a new element, when push and pop are frequents.
- Shared memory programming
- 3 threads, each having their own pool of unused elements.

The ABA problem

- The scenario starts
  - Thread 0
    - old→null
    - new→null
    - pool→null
  - Thread 1
    - old→null
    - new→null
    - pool→null
  - Thread 2
    - old→null
    - new→null
    - pool→null
- shared→A→B→C→null

The ABA problem

- The scenario starts
- Thread 0 pops A, preempted before CAS(head, old=A, new=B)
- shared→A→B→C→null

- Thread 0
  - old→A
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  - old→null
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The ABA problem

- The scenario starts
- Thread 0 pops A, preempted before CAS(head, old=A, new=B)
- Thread 1 pops A, succeeds

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  - new→B
  - pool→A→null
- Thread 2
  - old→null
  - new→null
  - pool→null

- shared→B→C→null

The ABA problem

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- Thread 1 pops A, succeeds
- Thread 2 pops B, succeeds

- Thread 0
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  - new→B
  - pool→null
- Thread 1
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- Thread 2
  - old→B
  - new→C
  - pool→B→null

- shared→C→null

The ABA problem

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- Thread 0 pops A, preempted before CAS(head, old=A, new=B)
- Thread 1 pops A, succeeds
- Thread 2 pops B, succeeds
- Thread 1 pushes A, succeeds

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- Thread 1
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  - pool→null
- Thread 2
  - old→B
  - new→C
  - pool→B→null

- shared→A→C→null

The ABA problem

- The scenario starts
- Thread 0 pops A, preempted before CAS(head, old=A, new=B)
- Thread 1 pops A, succeeds
- Thread 2 pops B, succeeds
- Thread 1 pushes A, succeeds
- Thread 0 performs CAS(head, old=A, new=B)

- shared→B→null

- Thread 0
  - old→A
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  - old→C
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- Thread 2
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The ABA problem

- The scenario starts
- Thread 0 pops A, preempted before CAS(head, old=A, new=B)
- Thread 1 pops A, succeeds
- Thread 2 pops B, succeeds
- Thread 1 pushes A, succeeds
- Thread 0 performs CAS(head, old=A, new=B)
- The shared stack should contain C element only, but head points to B in Thread 2's recycling bin
  - shared→B→null

- Thread 0
  - old→A
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  - pool→A→null
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  - pool→null
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The ABA problem

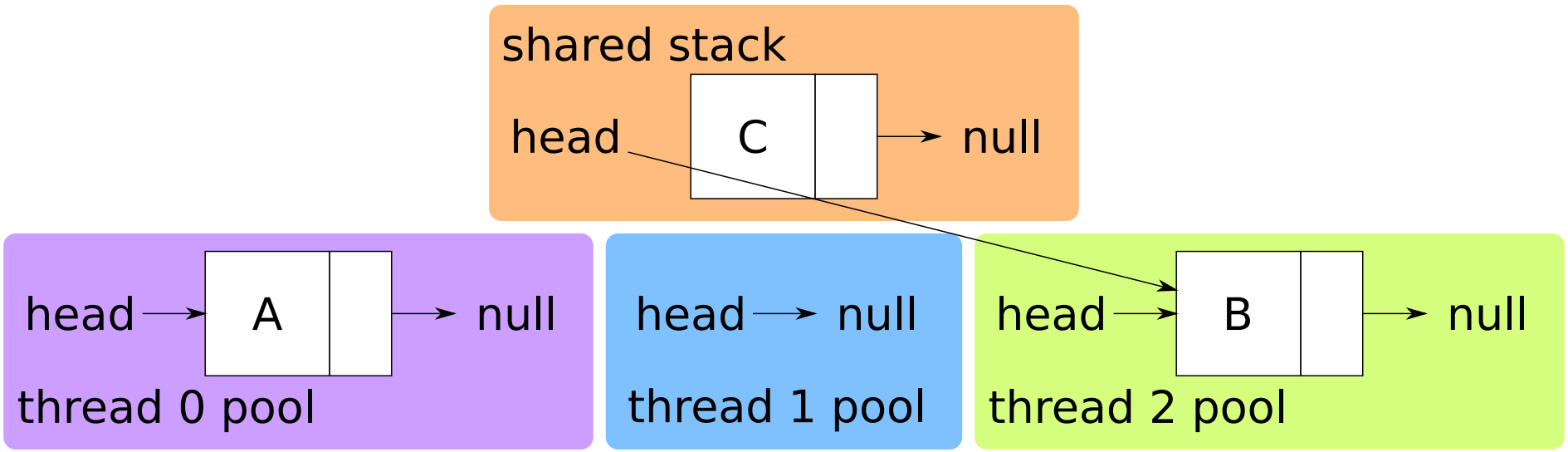

Figure: The shared stack should contain C element only, but head points to B in Thread 2's recycling bin.

Lab 2: Directions

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  - Warning: malloc/free operations expensive: make sure they don't occur in performance test
- Get more details and hints in the lab compendium

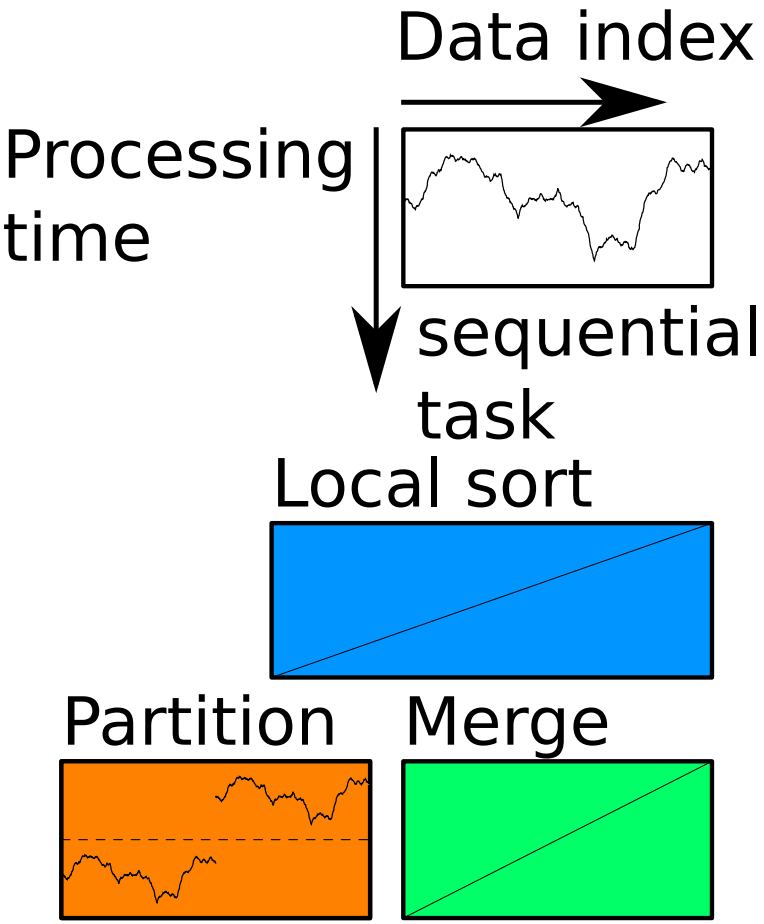
Lab 3: Parallel sorting

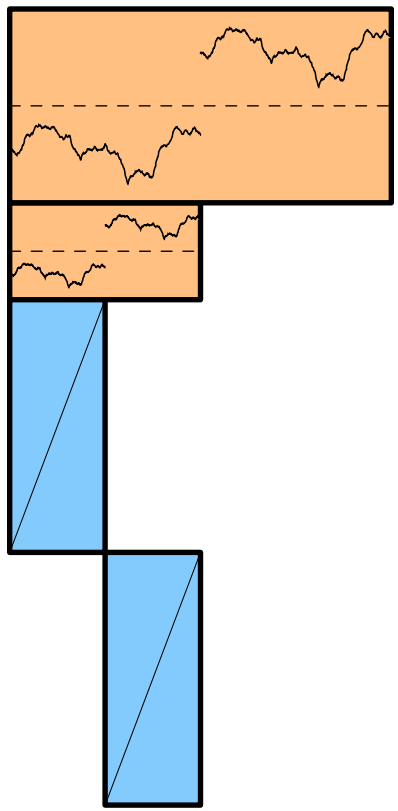
- Implement or optimize an existing sequential sort implementation
- Parallelize with shared memory approach (pthread or openMP)
- Parallelize with Streaming (Drake)
- Test your sorting implementation with various situations
  - Random, ascending, descending or constant input
  - Small and big input sizes
  - Other tricky situations you may imagine
- Built-in sorting functions (qsort(), std::sort()) are forbidden
  - May rewrite it for better performance
- Lab demo: describe the important techniques that accelerate your implementation.

Base sequential sort

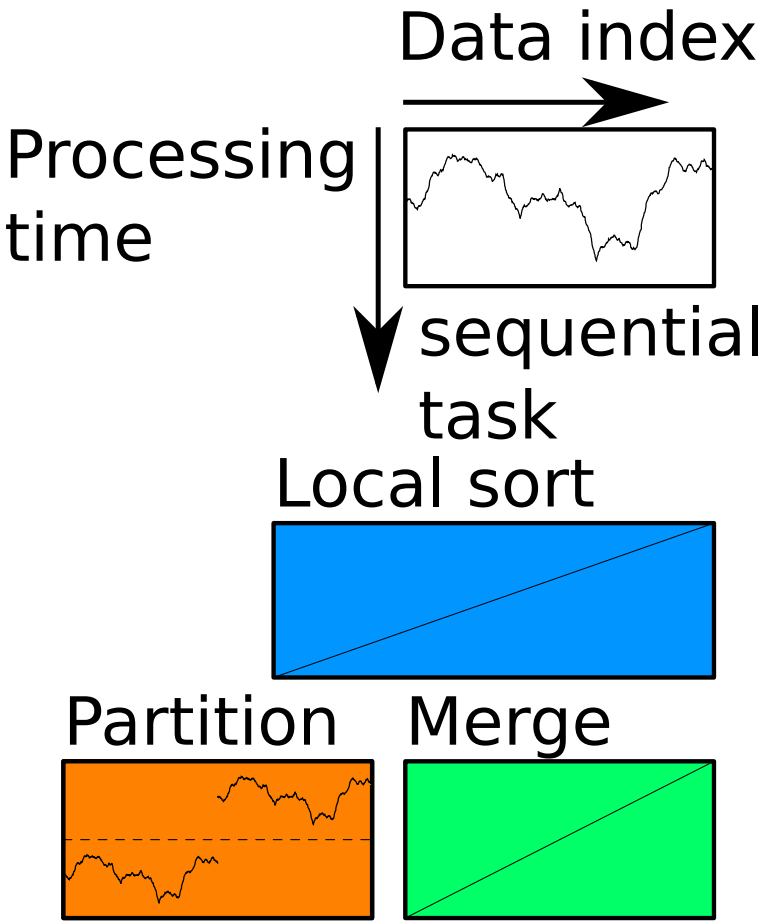
```
simple_quicksort(array, size) {
        pivot = array[size / 2];
        for(i = 0; i < size; i++) {}
                if(array[i] < pivot) {
                        left[left_size] = array[i];
                        left_size++;
                } else if(array[i] > pivot) {
                        right[right_size] = array[i];
                        right_size++;
                } else
                        pivot_count++;
        }
        simple_quicksort(left, left_size);
        simple_quicksort(right, right_size);
        memcpy(array, left, left_size * sizeof(int));
        for(i = left_size; i < left_size + pivot_count; i++)
                array[i] = pivot;
        memcpy(array + left_size + pivot_count, right, right_size * sizeof(int));
}
```

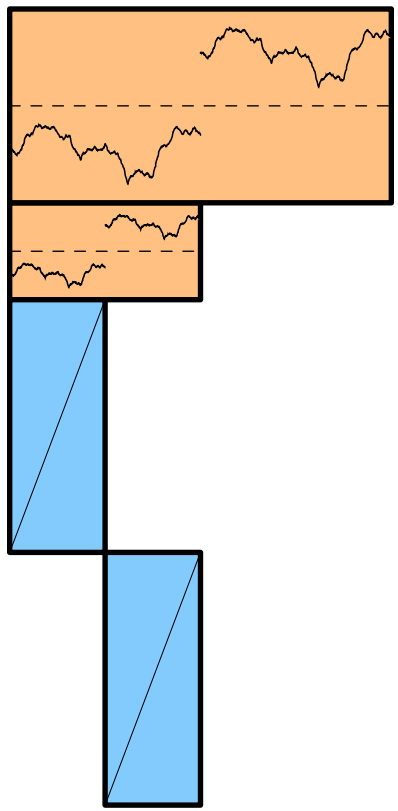
Base sequential sort

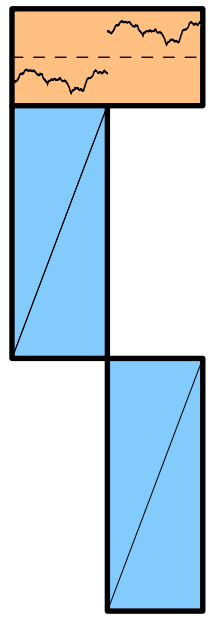




Base sequential sort



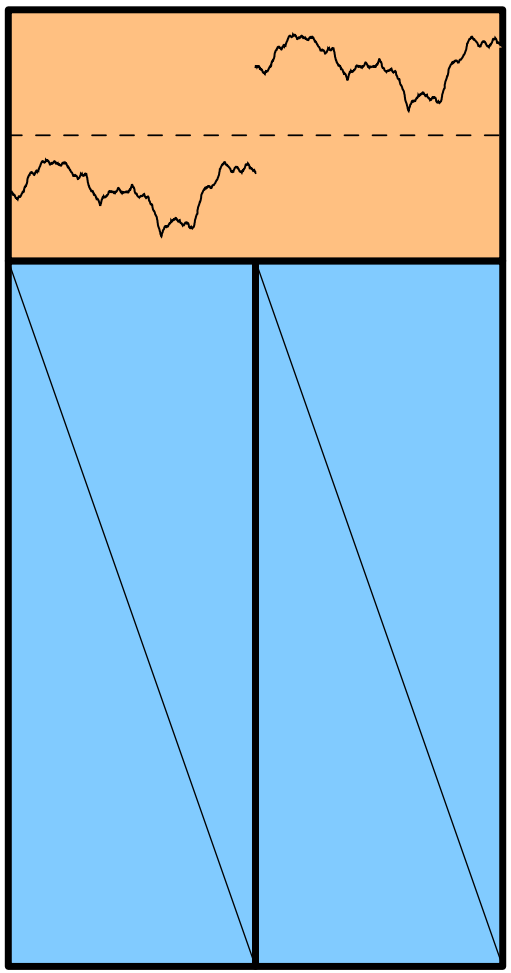




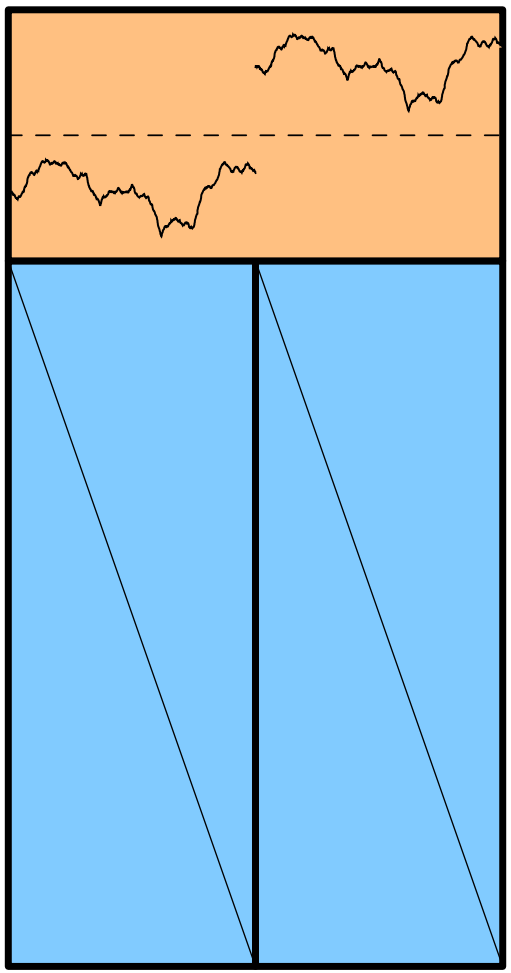
Parallelization opportunities

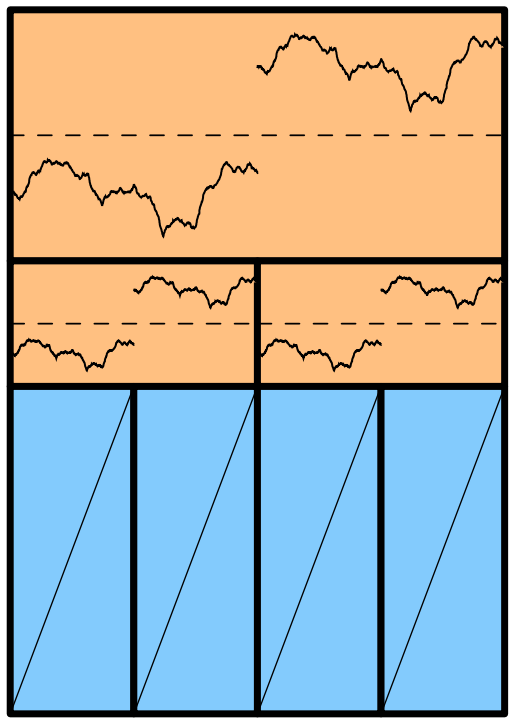
- Parallelization opportunities
  - Recursive calls
  - Computing pivots
  - Merging, if necessary
- Smart solutions challenging to implement
  - In-place quicksort: false sharing
  - Parallel sampling/merging: synchronization
  - Follow the KISS rule
- Avoid spawning more threads than the computer has cores
- Use data locality with caches and cache lines

Simple parallelization

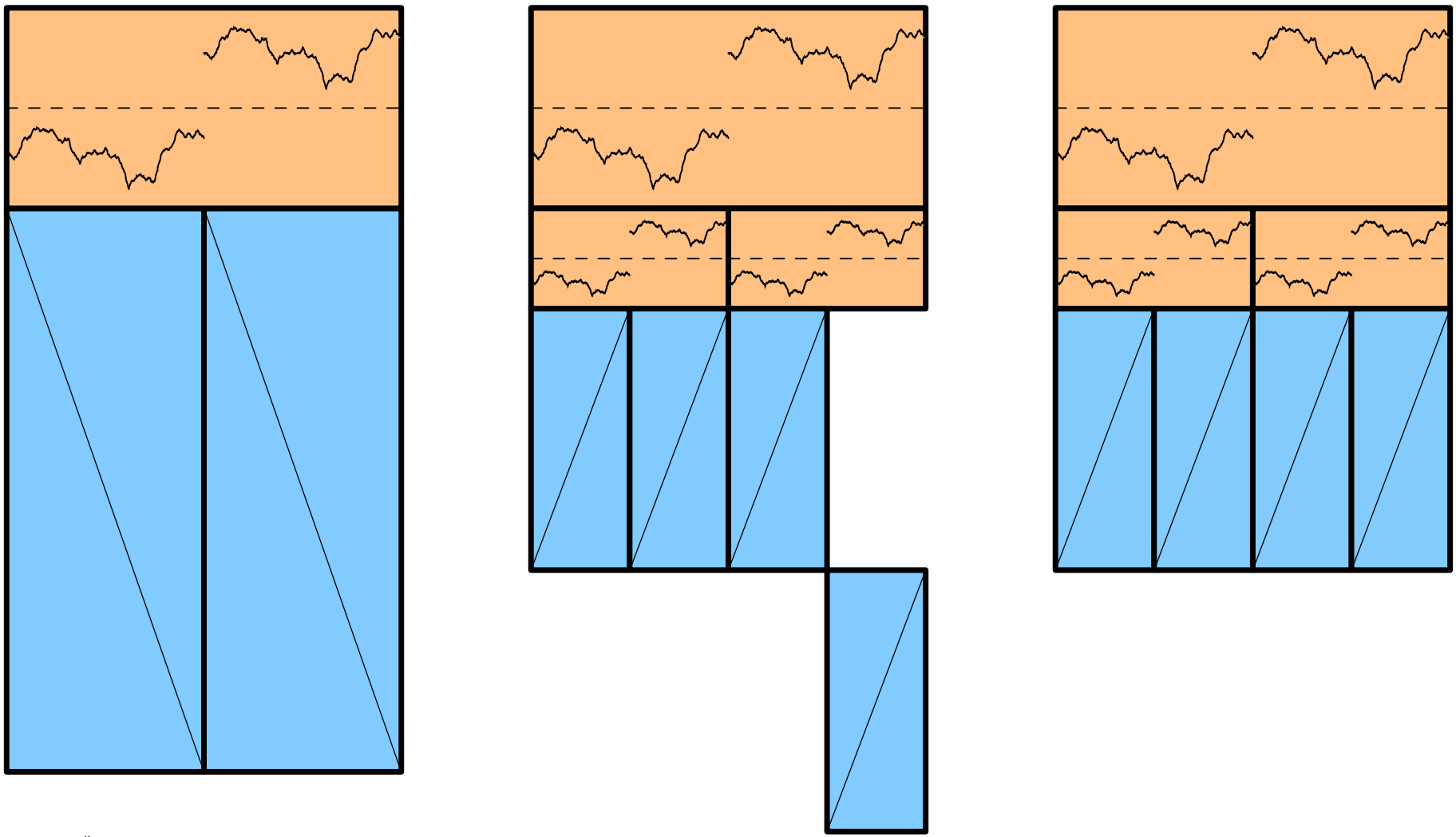


Simple parallelization





Simple parallelization



Parallel Quicksort sort with 3 cores

Can only efficiency use power of two number of cores.
How to use three cores efficiently?

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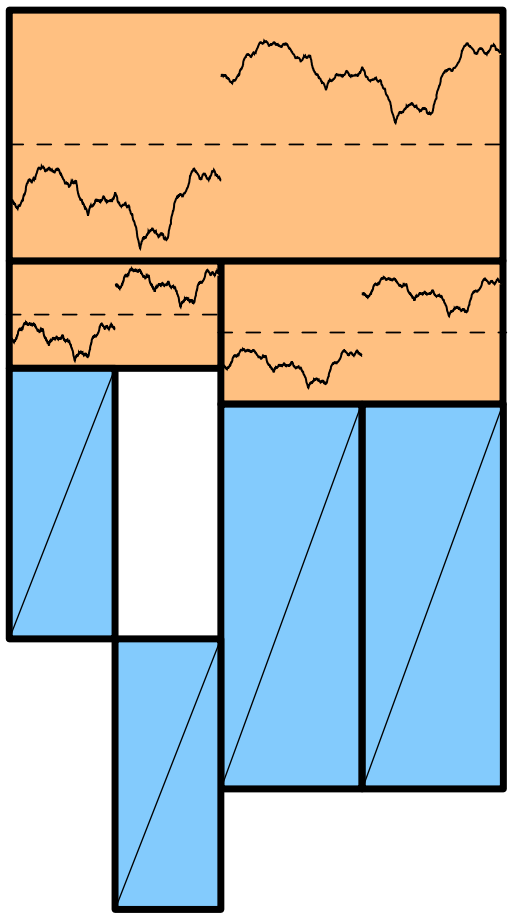
How to use three cores efficiently?

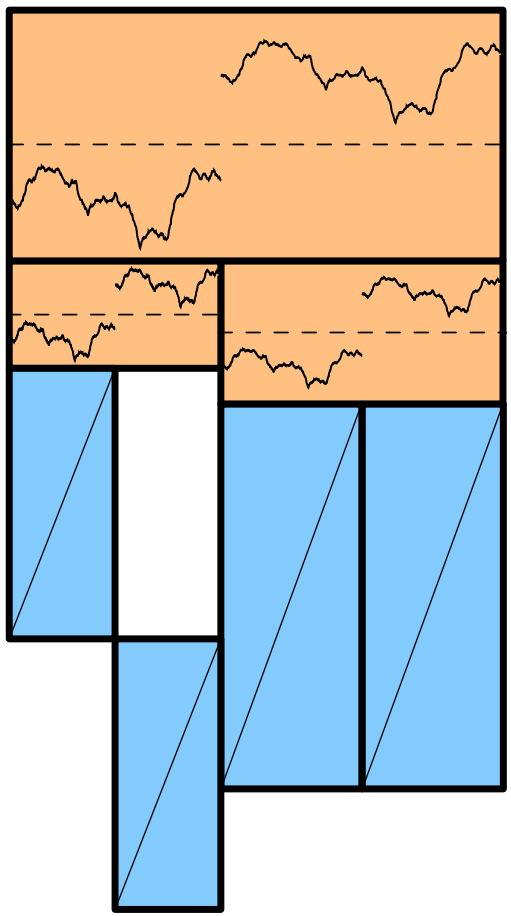
- Choose pivot to divide buffer into unequal parts

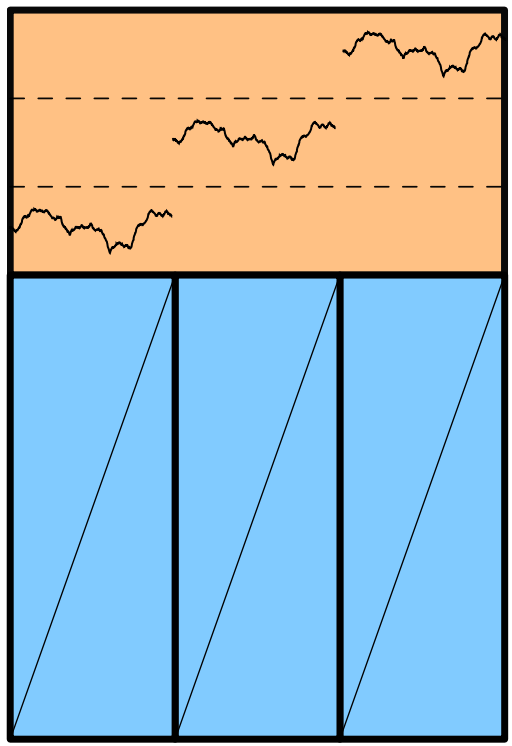


Parallel Quicksort sort with 3 cores

Can only efficiency use power of two number of cores.
How to use three cores efficiently?

- Choose pivot to divide buffer into unequal parts
- Partition and recurse into 3 parts (sample sort)

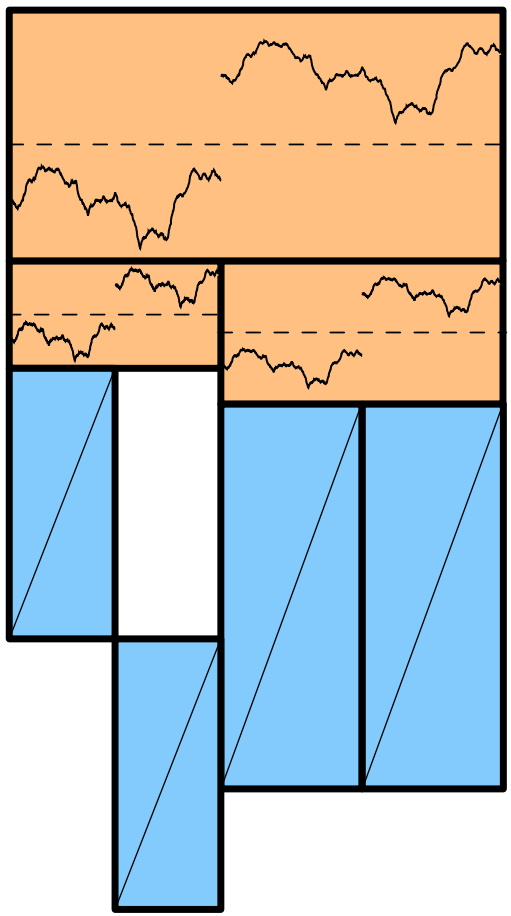


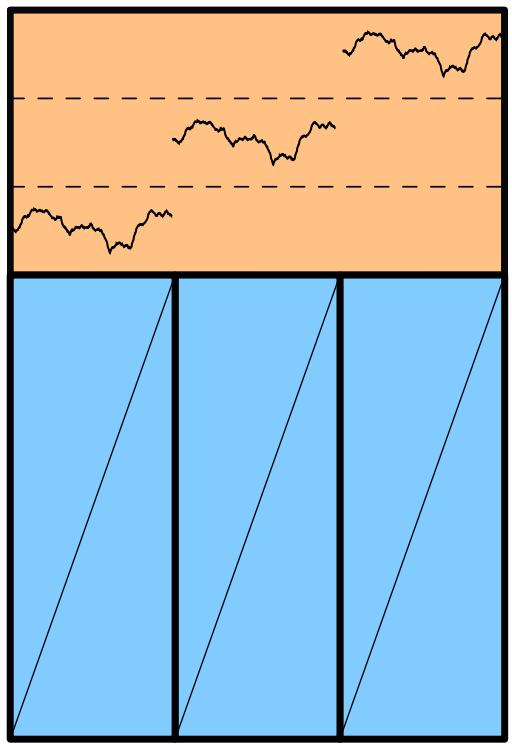


Parallel Quicksort sort with 3 cores

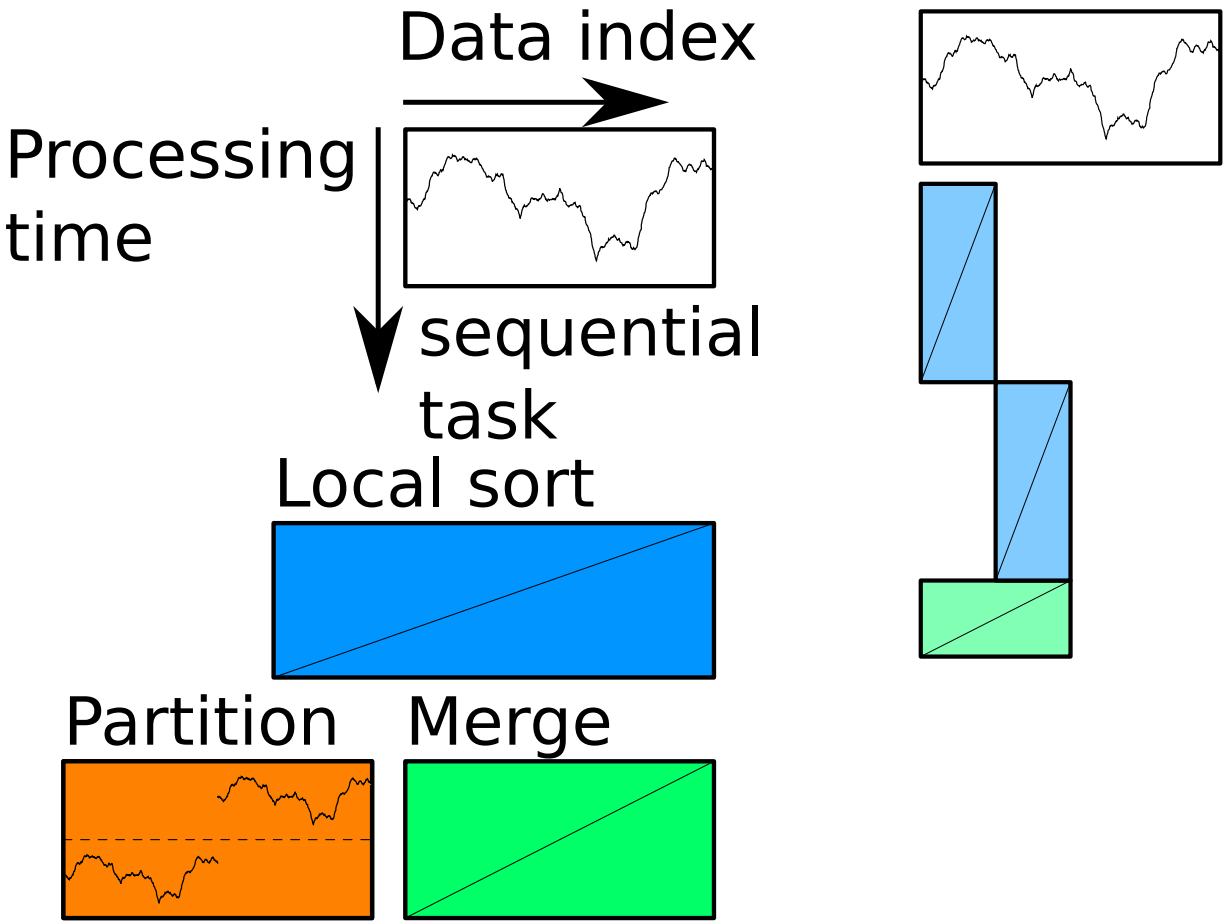
Can only efficiency use power of two number of cores.
How to use three cores efficiently?

- Choose pivot to divide buffer into unequal parts
- Partition and recurse into 3 parts (sample sort)
- Makes implementation harder

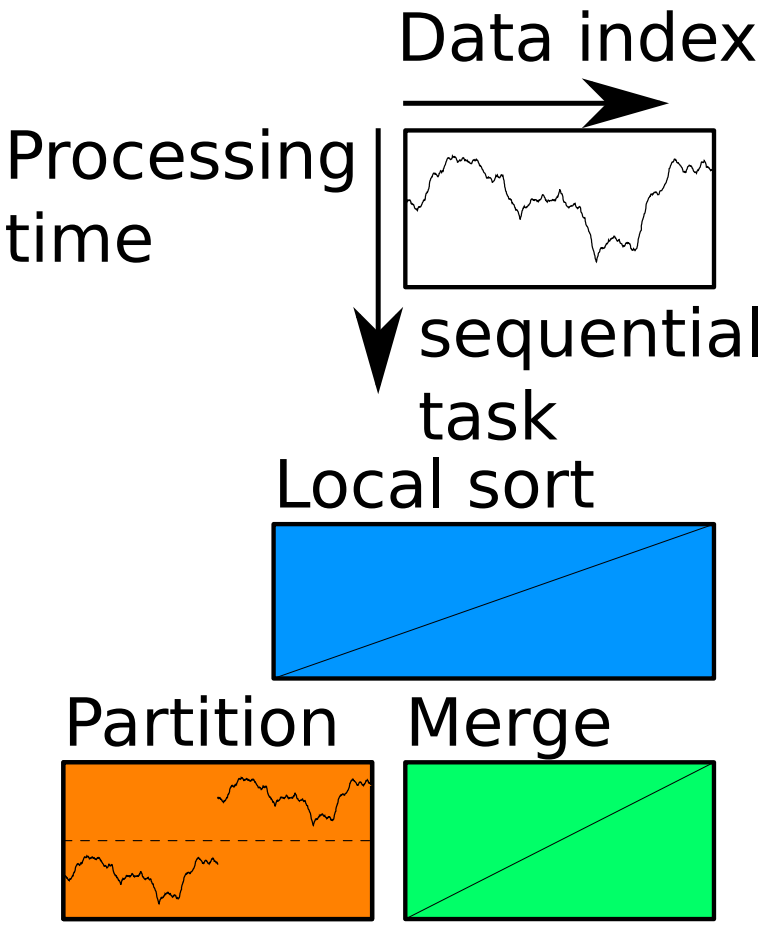




Mergesort


Data index
Processing time
sequential task
Local sort
Partition
Merge

Mergesort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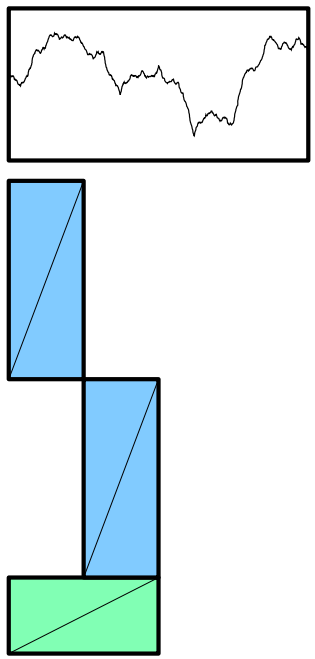
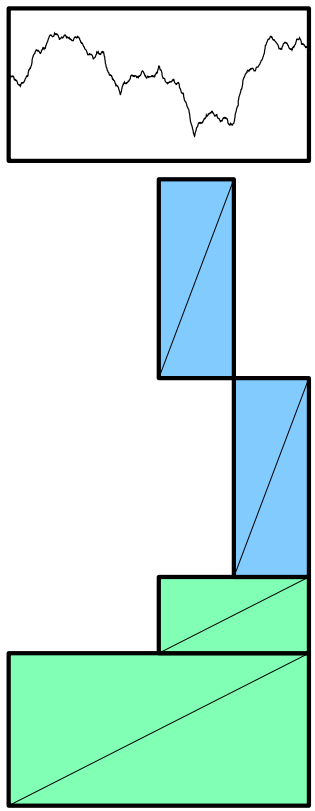
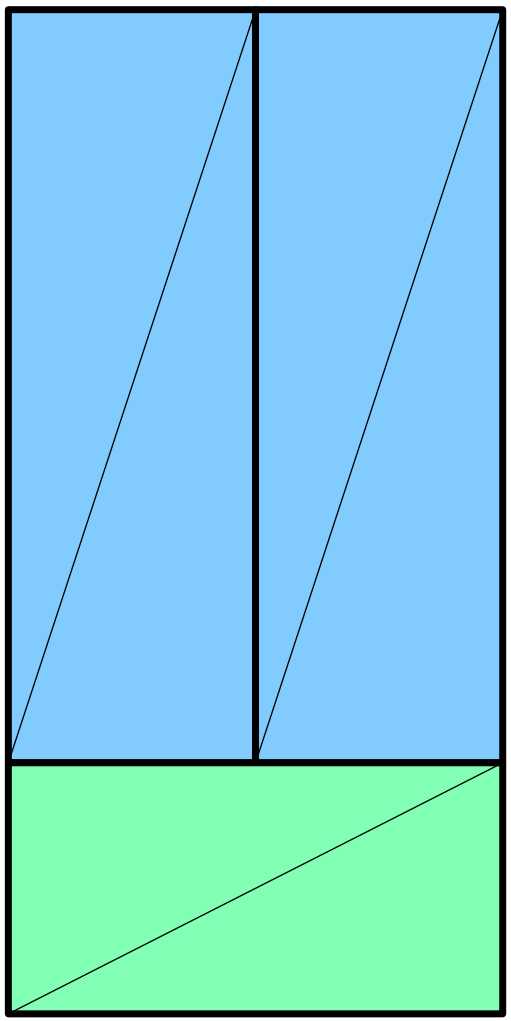
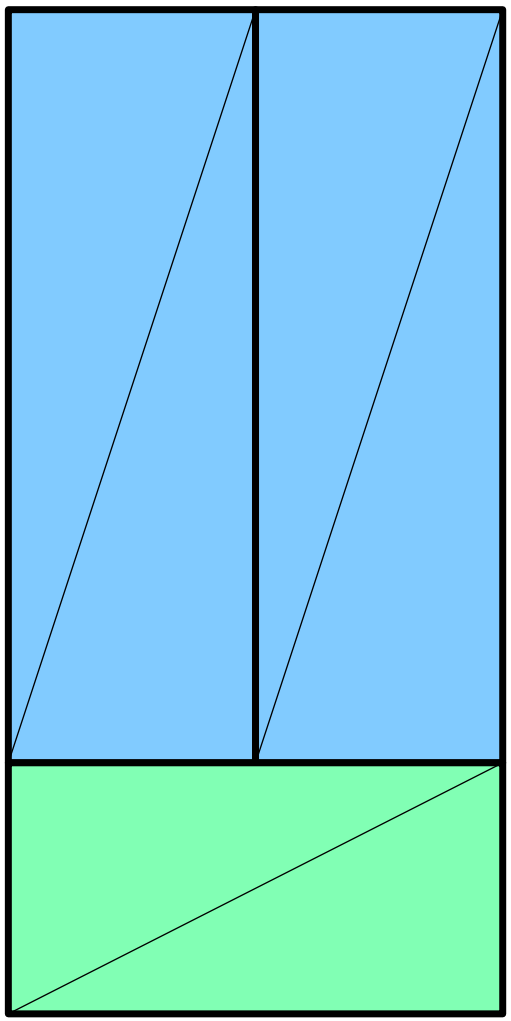


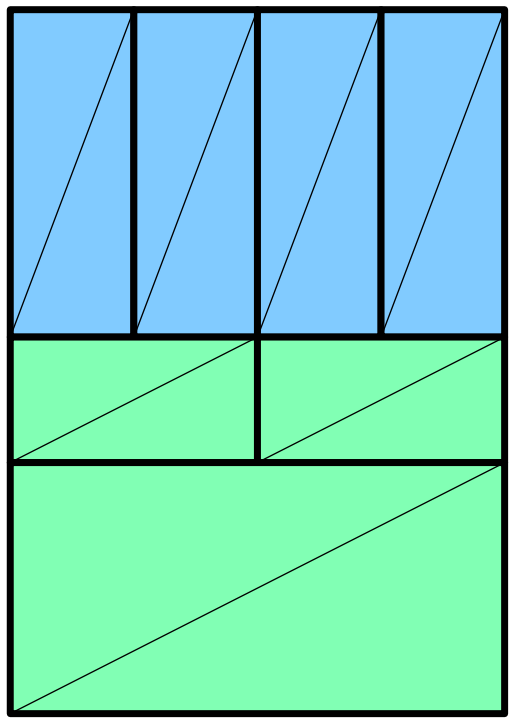


Simple Mergesort Parallelization



Simple Mergesort Parallelization





Parallel Mergesort with 3 cores

Can only efficiency use power of two number of cores.
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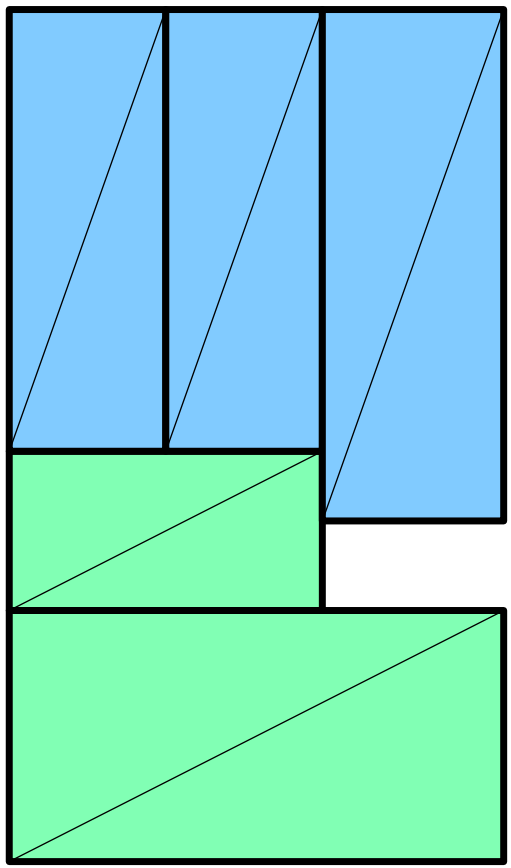
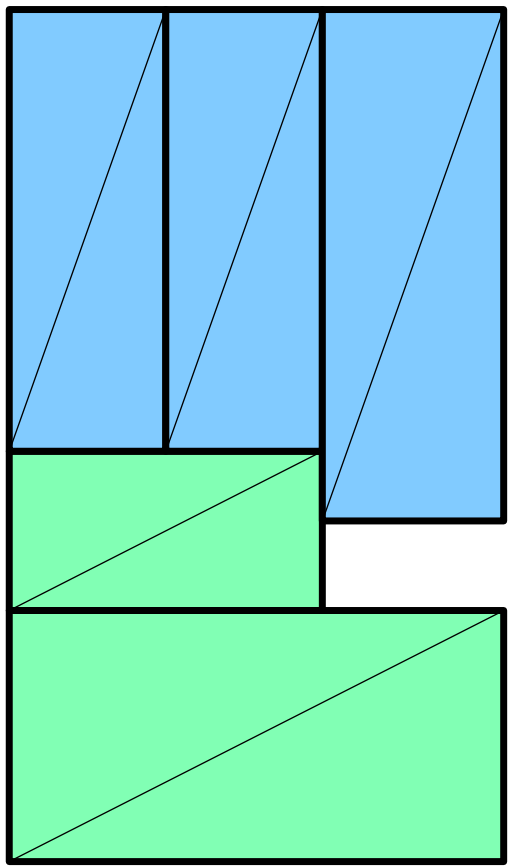
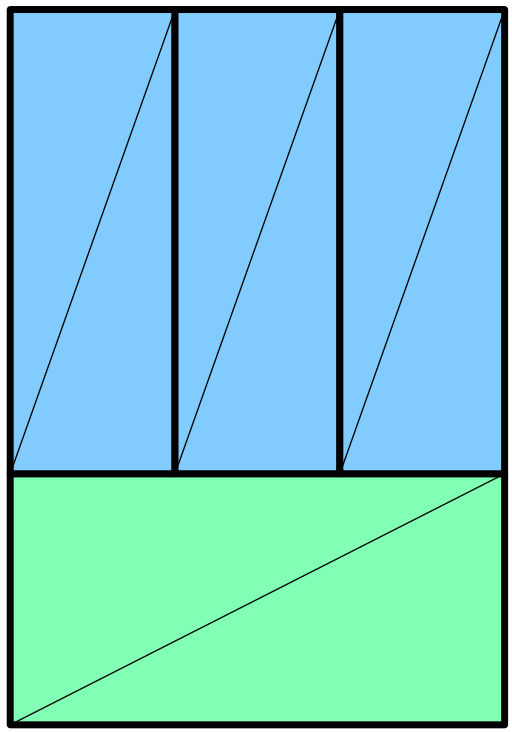


Parallel Mergesort with 3 cores

Can only efficiency use power of two number of cores.
How to use three cores efficiently?

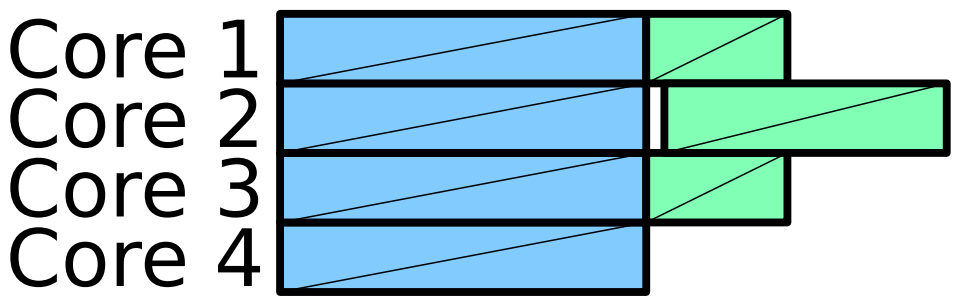
- Divide buffer into 2 unequal parts
- Partition and recurse into 3 parts and 3-way merge





Pipelined parallel mergesort

Classic parallelism: start a task when the previous one is done Pipeline parallelism: Run next merging task as soon as possible



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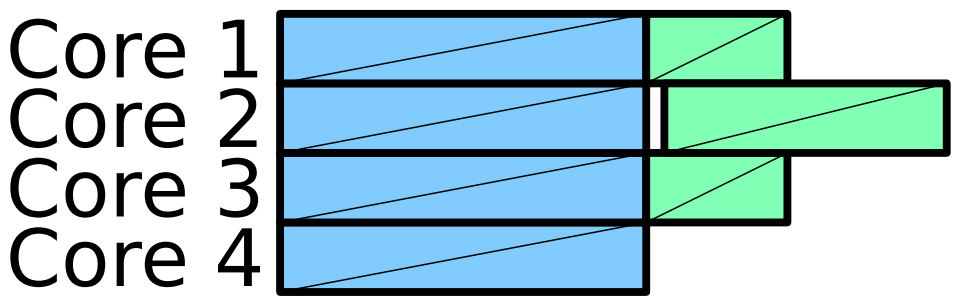

- Even more speedup

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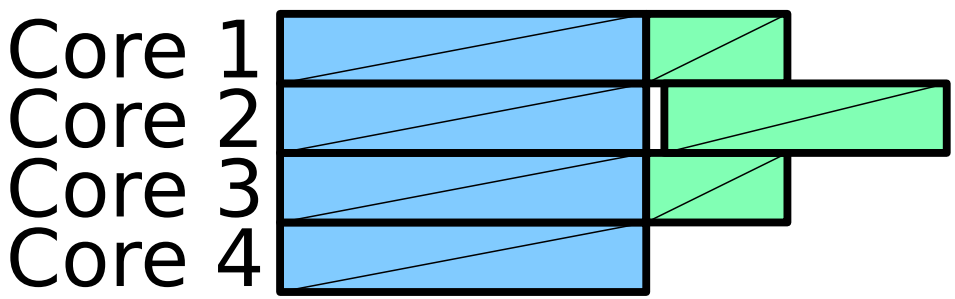

- Even more speedup
- Difficult to implement manually

Pipeline parallelism

Related research since the 60’

- Program verifiability

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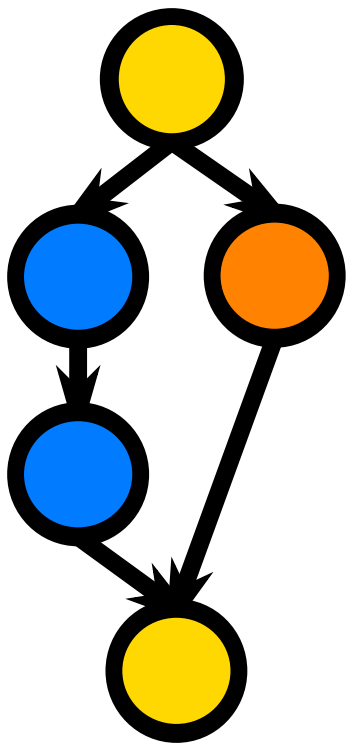

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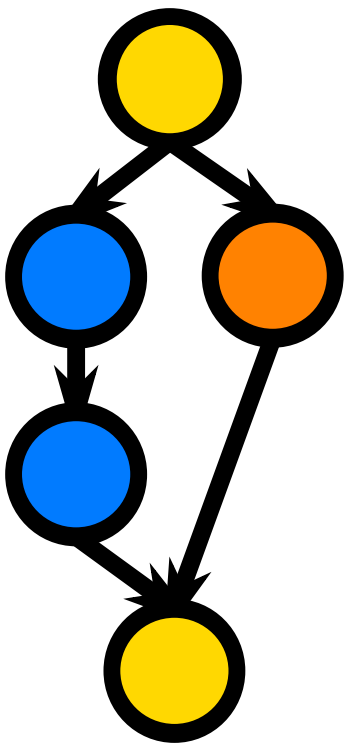

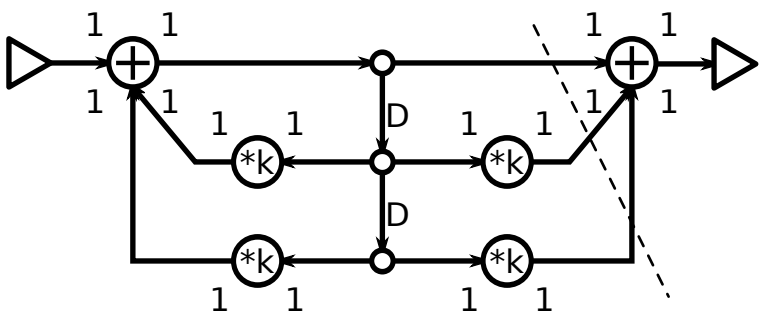

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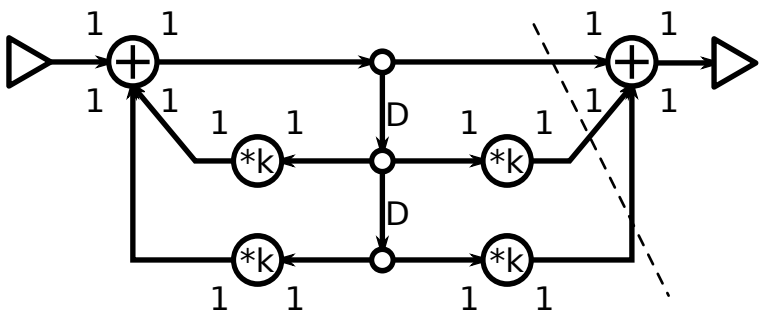

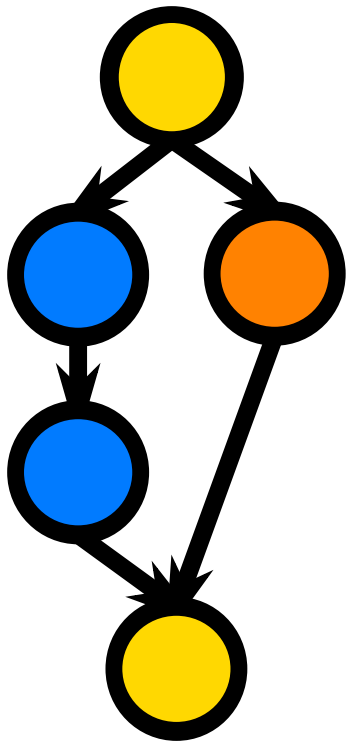

Classic versus stream

Most programming languages unsuitable to parallelism

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Stream programming

- (Mostly) sequential tasks
- Actual parallelism: scheduling
- No universal shared memory
- Natural to pipeline parallelism
- Communications with on-chip memories: on-chip pipelining

Scheduling

Optimize distribute tasks to cores

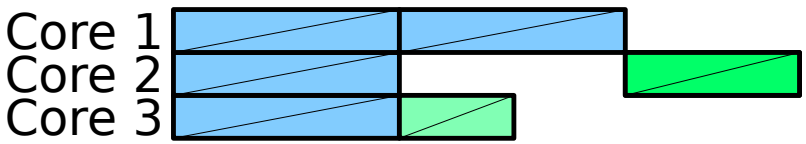
- For speed, energy, power or a compromise
- Sequential, moldable or malleable tasks
- Power management: DVFS, Sleeping states

Abundant research

- Longest Processing Time First (LPT)
- Crown Scheduling

Back to parallel merge

Classic parallelism



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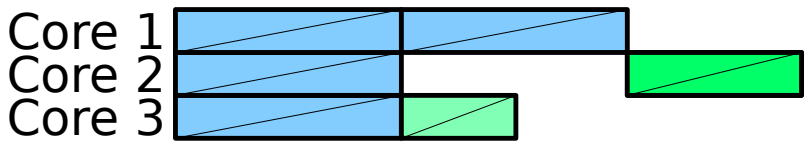
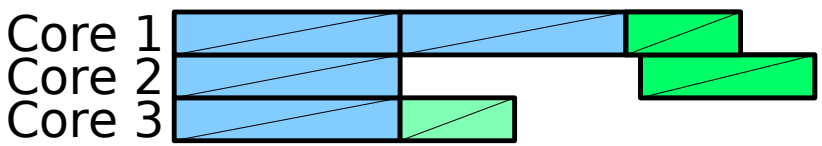


Pipelining (4 initial sorting tasks)



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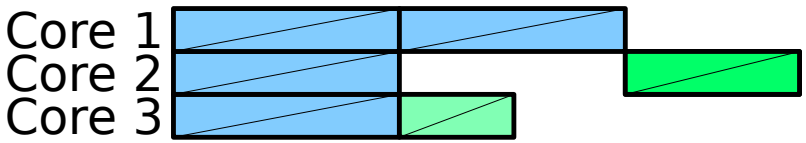

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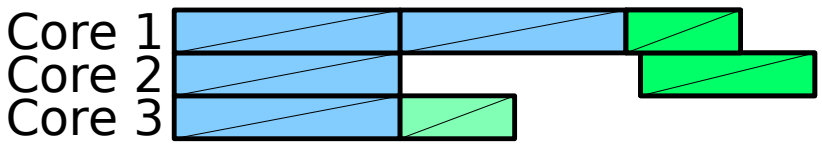

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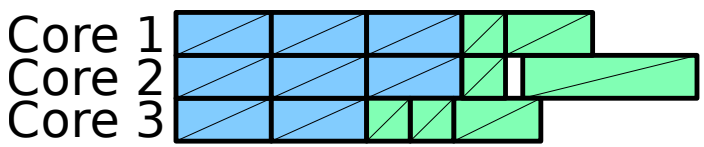

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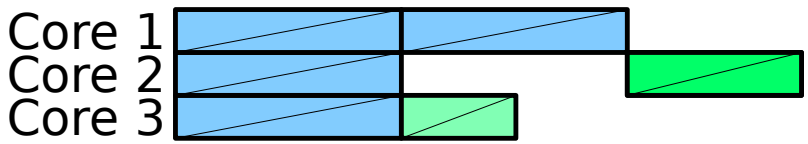

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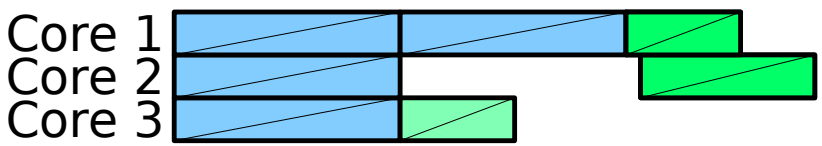

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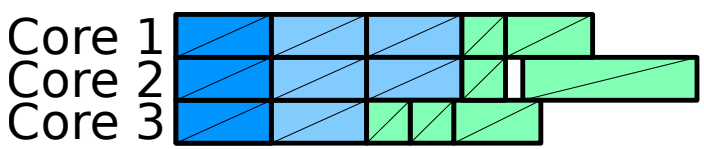

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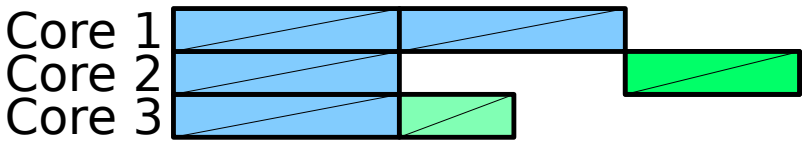

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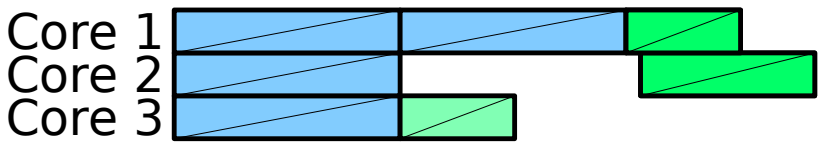

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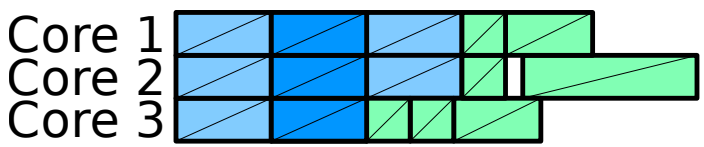

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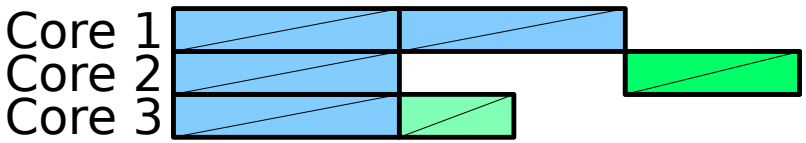

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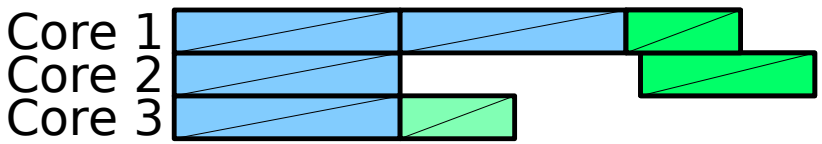

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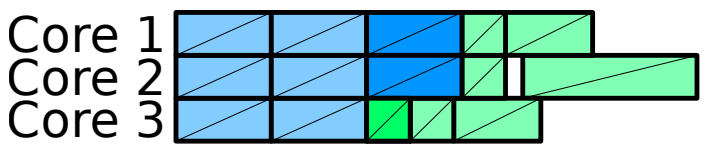

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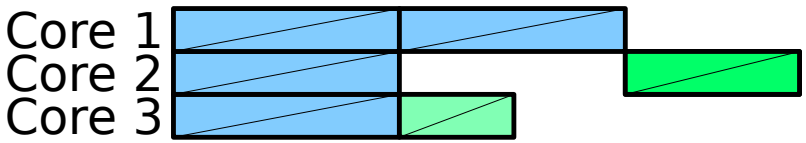

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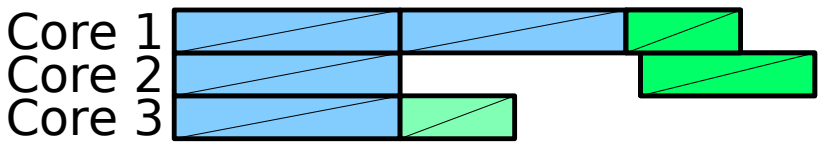

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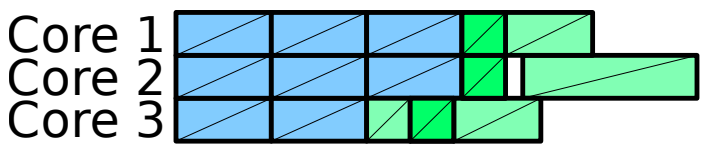

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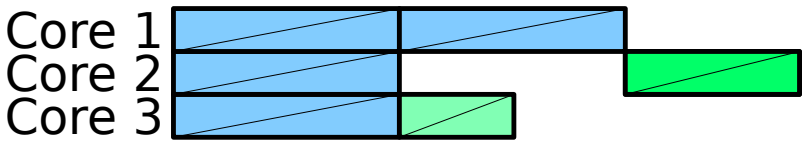

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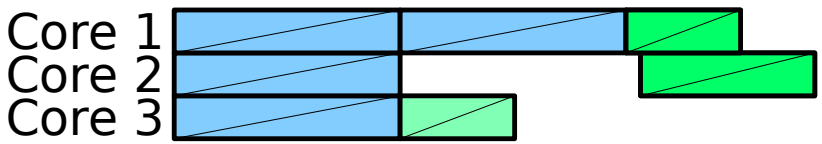

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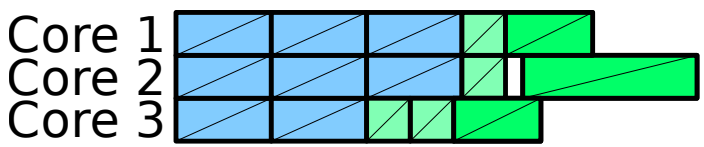
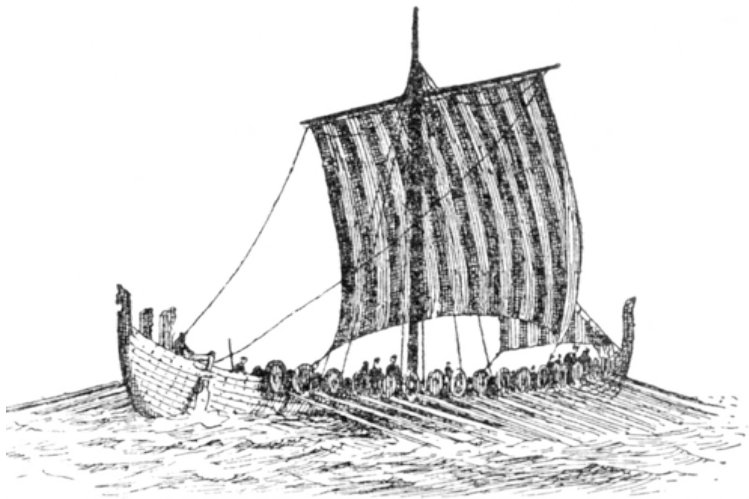
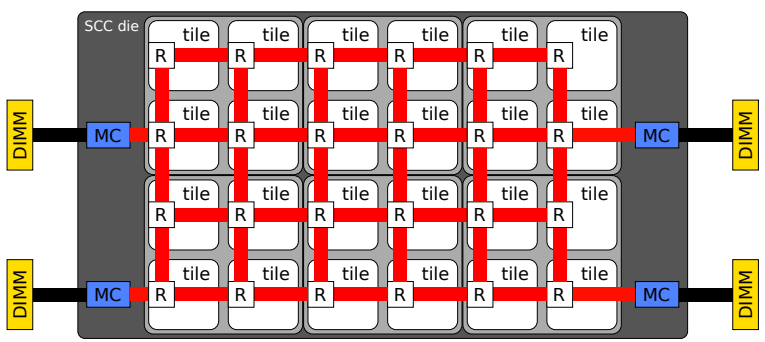


Drake

Drake: A C framework for Streaming Applications

- Separate design
  - Application
  - Platform





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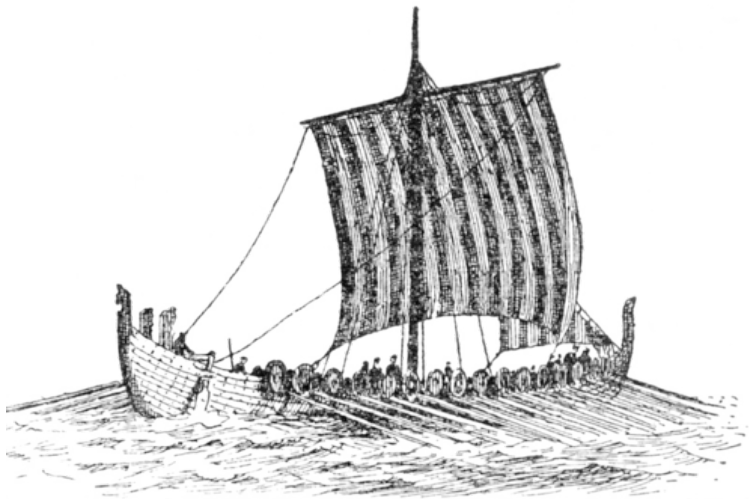

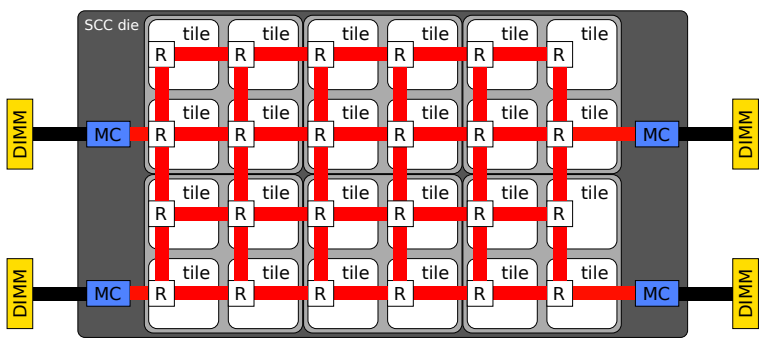

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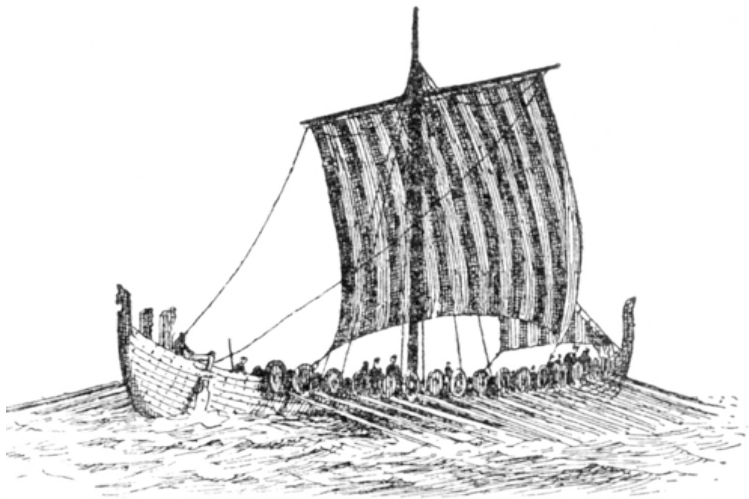

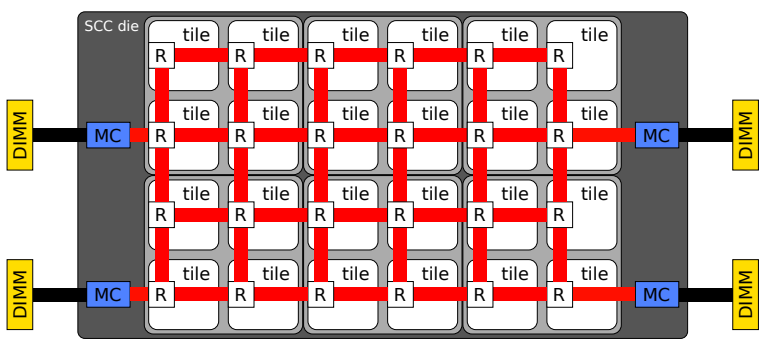

Drake

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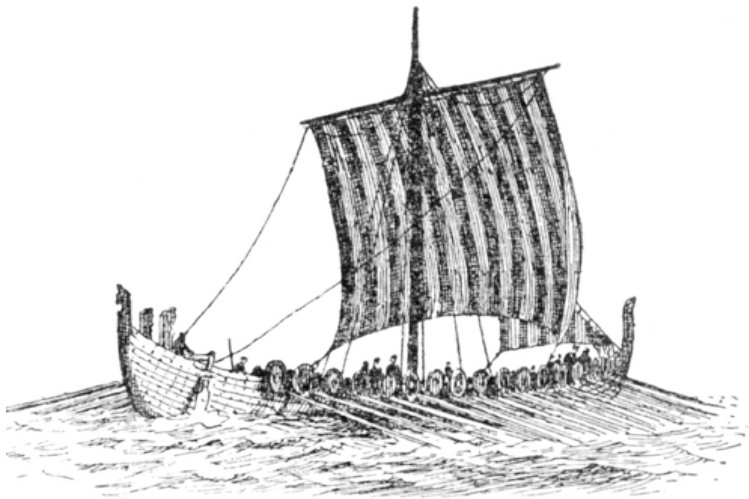
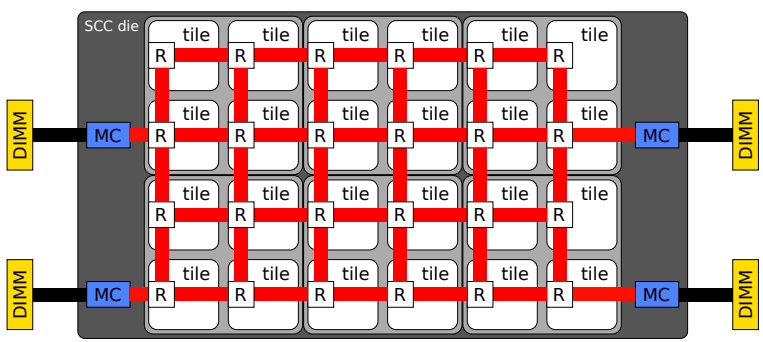
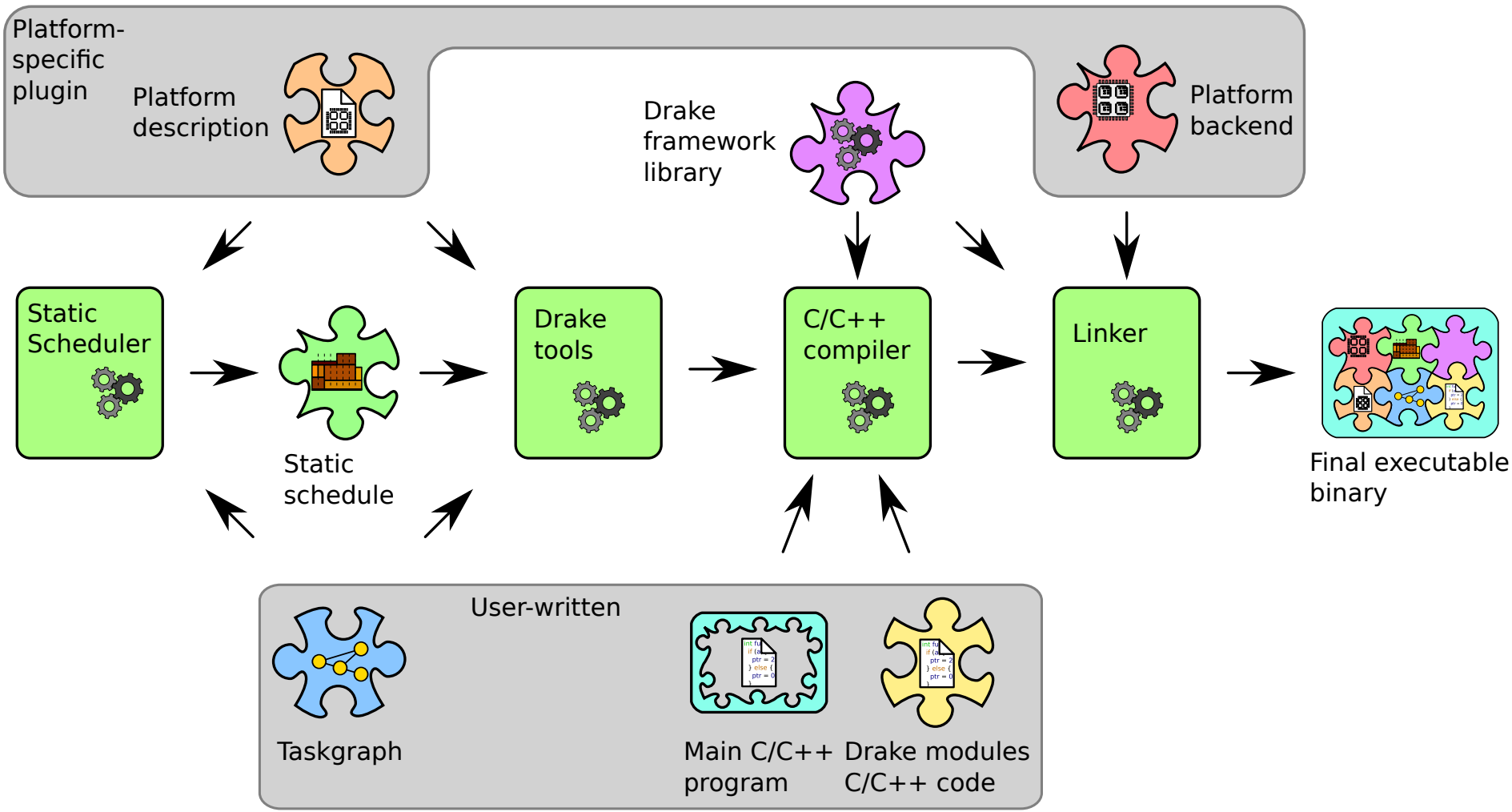
- Multi target
  - Intel SCC
  - Intel Xeon





Design with Drake



Lab 3: Directions

Part 1: Classic parallel sort

- Parallelize the sequential sort provided in src/sort.cpp. Keep it simple
- Optimize it so it can use 3 cores efficiently

Lab 3: Directions

Part 1: Classic parallel sort

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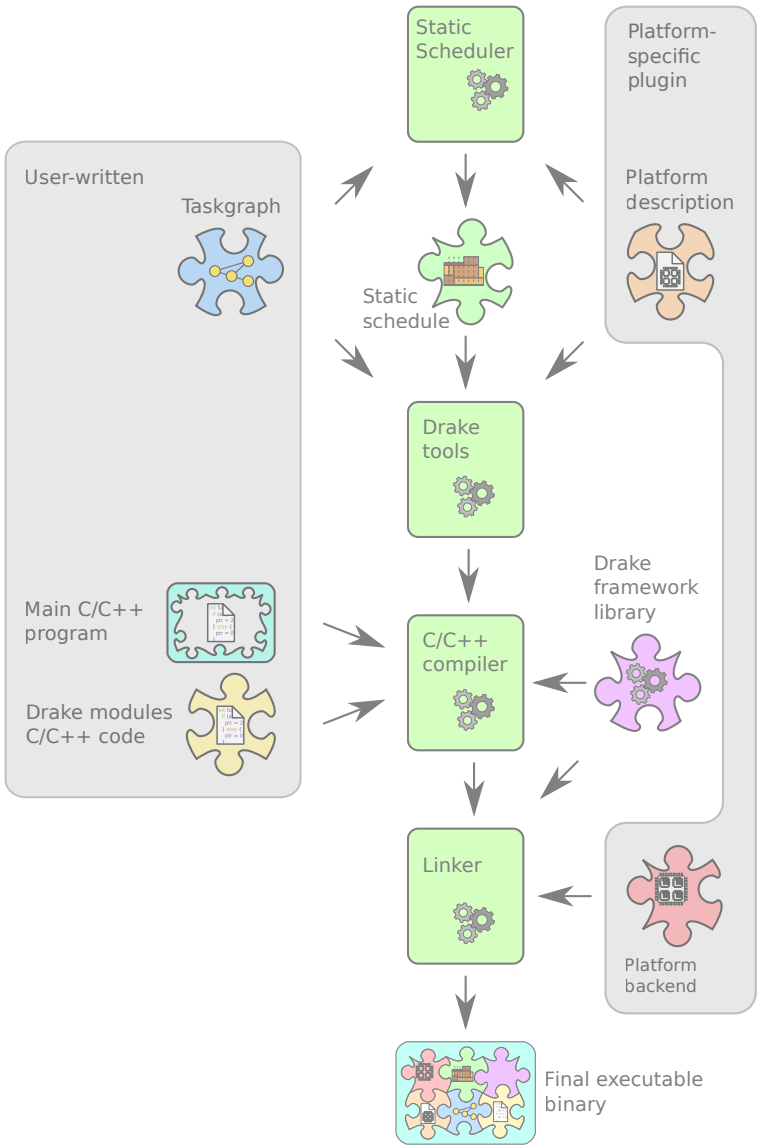
- Optimize it so it can use 3 cores efficiently

Part 2: Pipelined parallel mergesort using Drake

Lab3: Directions

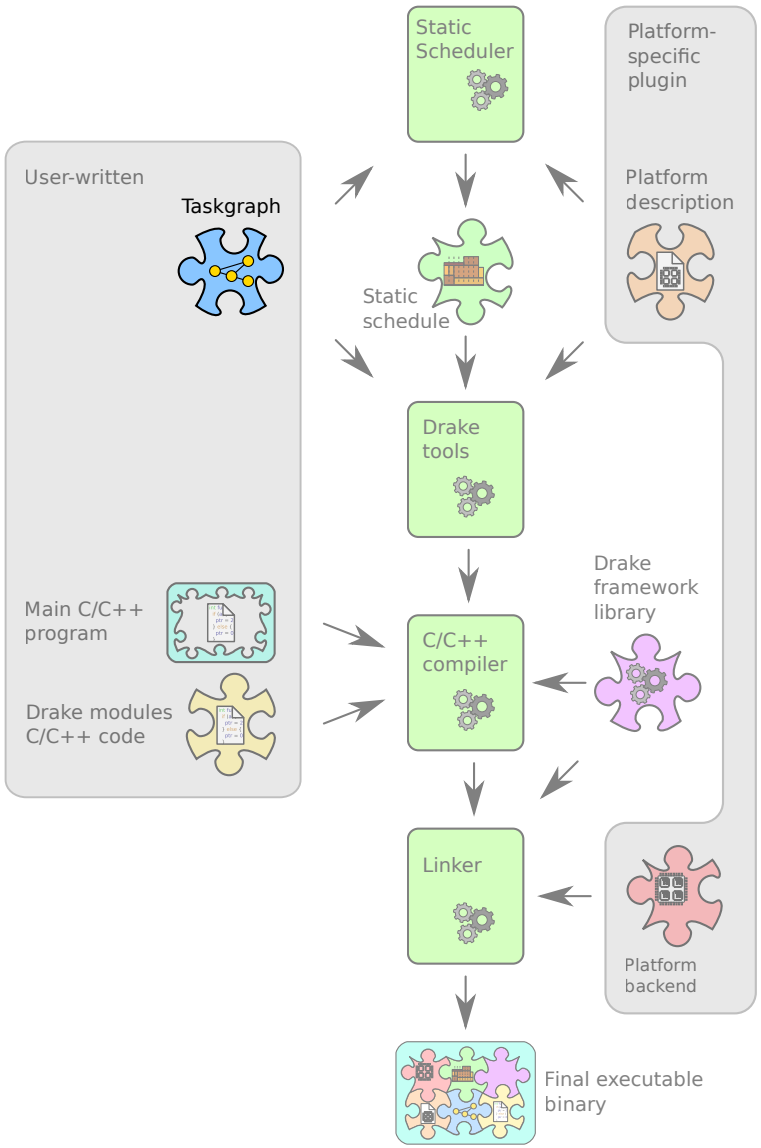
Development steps



Lab3: Directions

Development steps

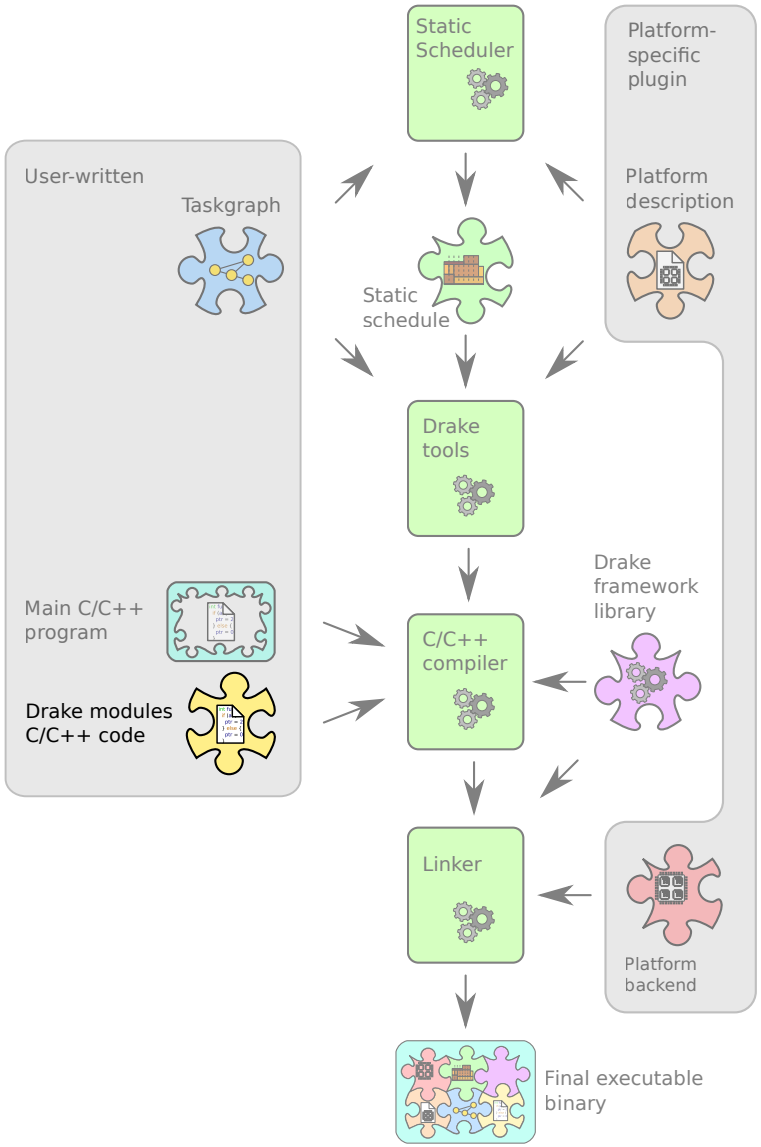
1. Describe streaming application
   - *src/merge*.graphml*



Lab3: Directions

Development steps

1. Describe streaming application
   - *src/merge*.graphml*
2. Write task code
   - *src/merge.c*



Lab3: Directions

Development steps

1. Describe streaming application
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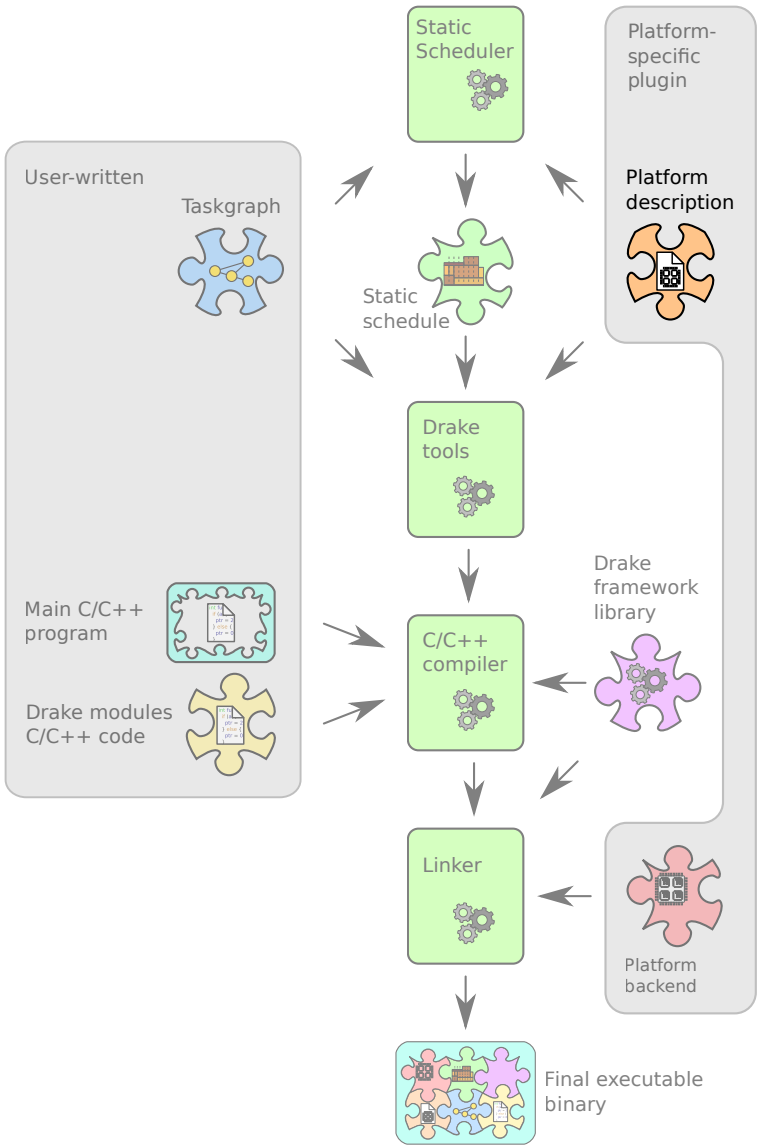
2. Write task code
   - *src/merge.c*
3. Describe target platform
   - *src/platform*.dat*



Lab3: Directions

Development steps

1. Describe streaming application
   - *src/merge*.graphml*
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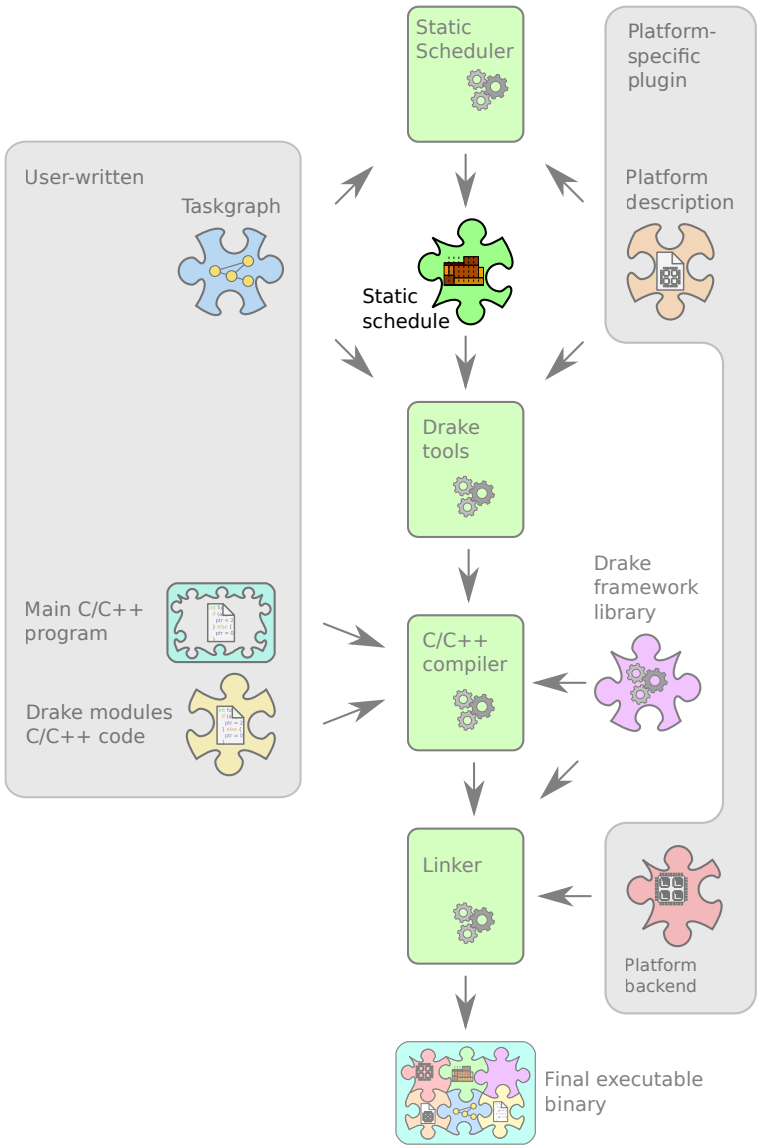
   - *src/merge.c*
3. Describe target platform
   - *src/platform*.dat*
4. Define schedule
   - *src/schedule*.dat*



Lab3: Directions

Development steps

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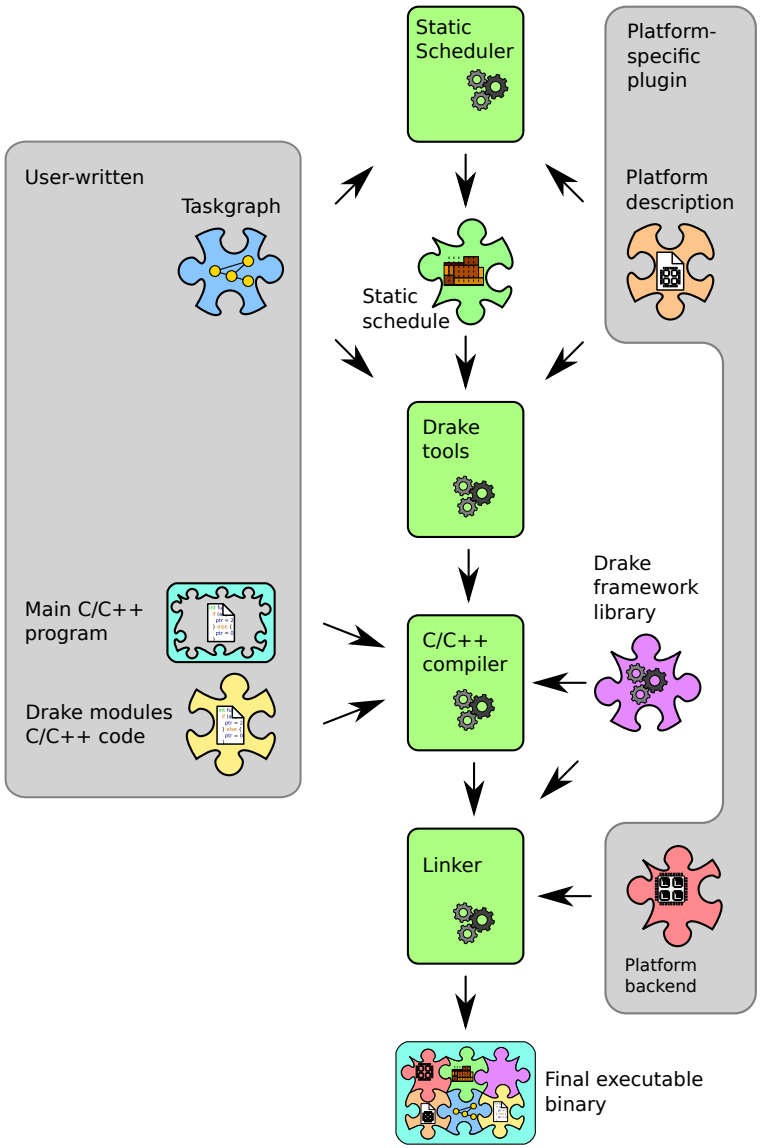
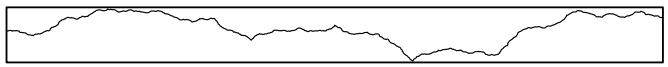
   - *src/merge*.graphml*
2. Write task code
   - *src/merge.c*
3. Describe target platform
   - *src/platform*.dat*
4. Define schedule
   - *src/schedule*.dat*
5. Compile application

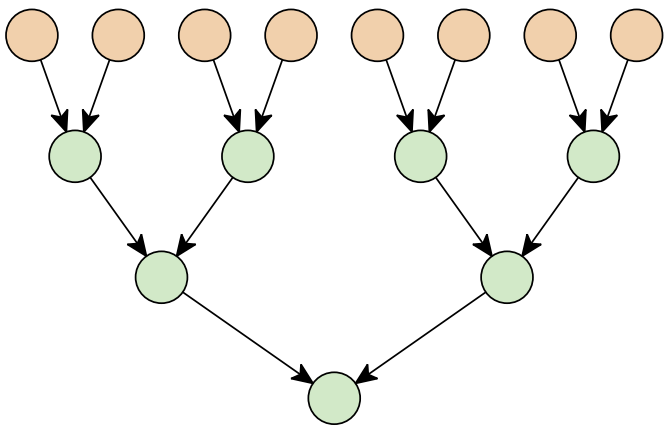


Describe Streaming Application

Describe Mergesort

- Split program into tasks

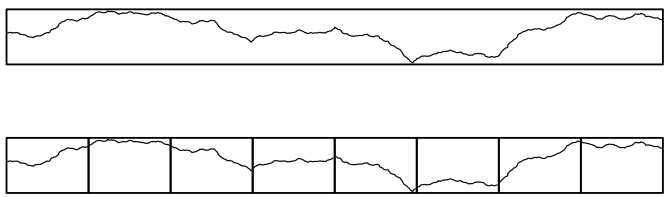


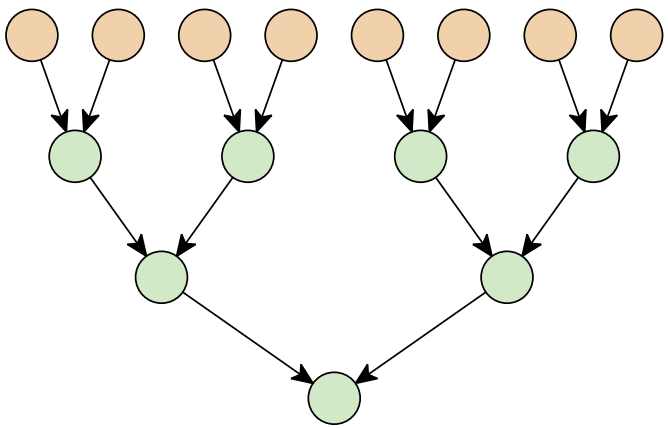


Describe Streaming Application

Describe Mergesort

- Split program into tasks
  - Partitioning

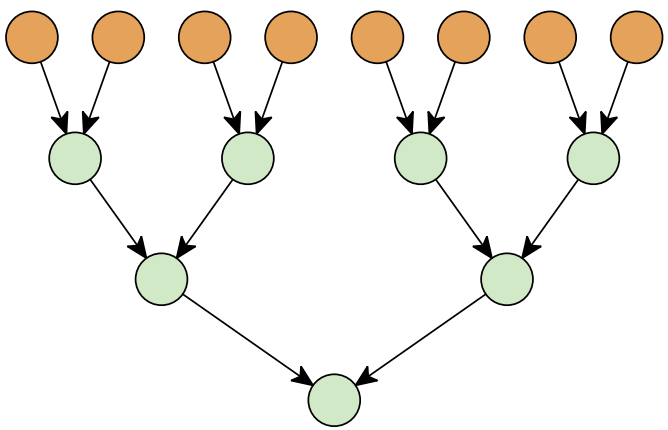


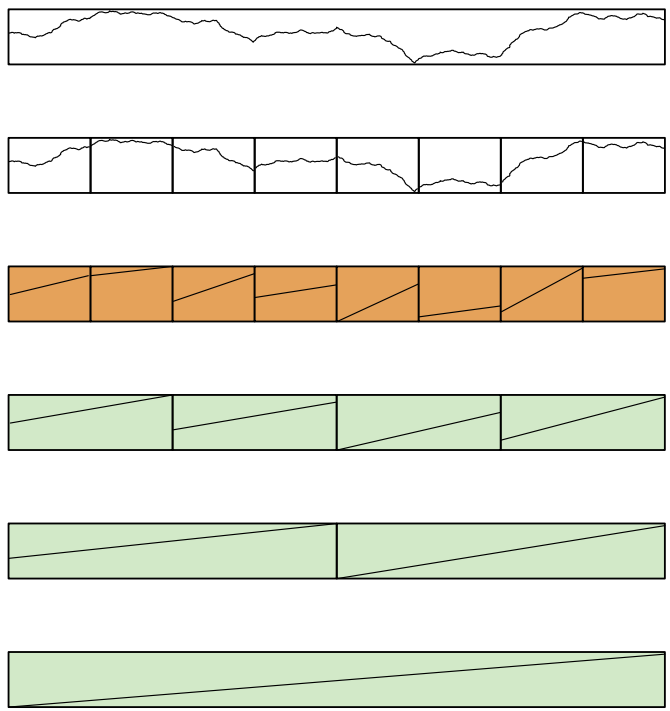


Describe Streaming Application

Describe Mergesort

- Split program into tasks
  - Partitioning
  - Presorting





Describe Streaming Application

Describe Mergesort

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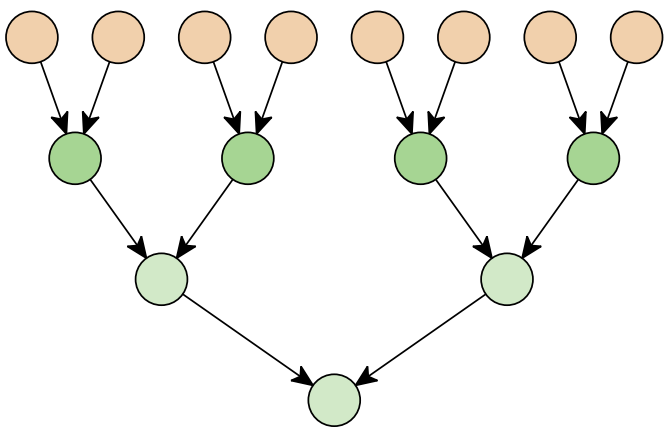

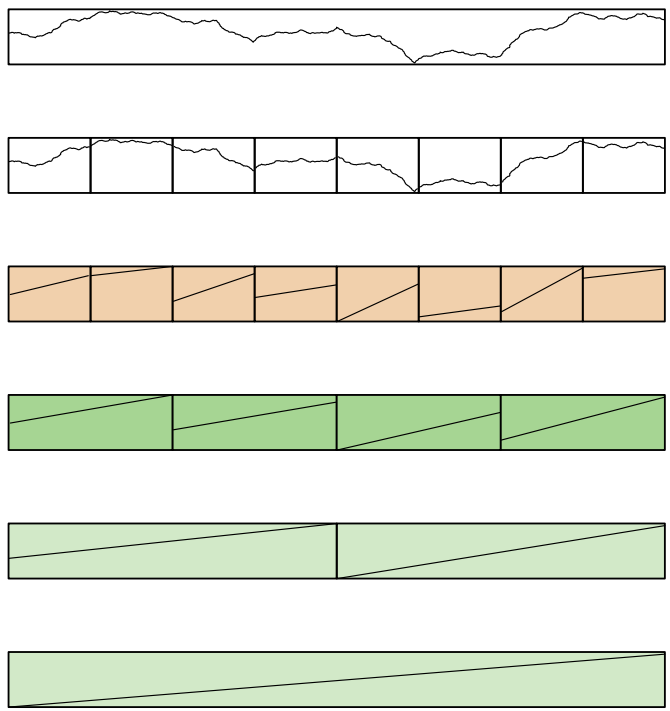

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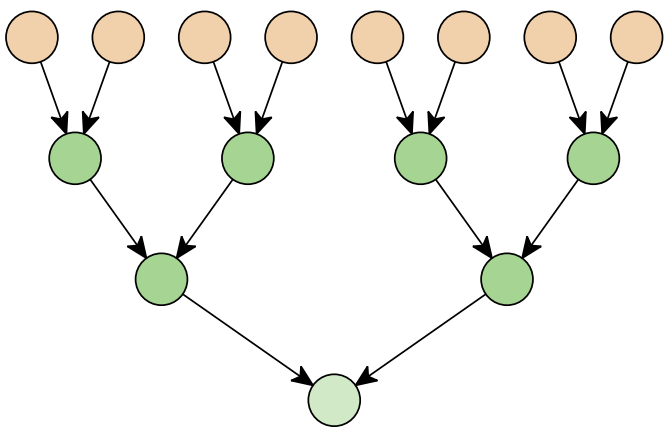

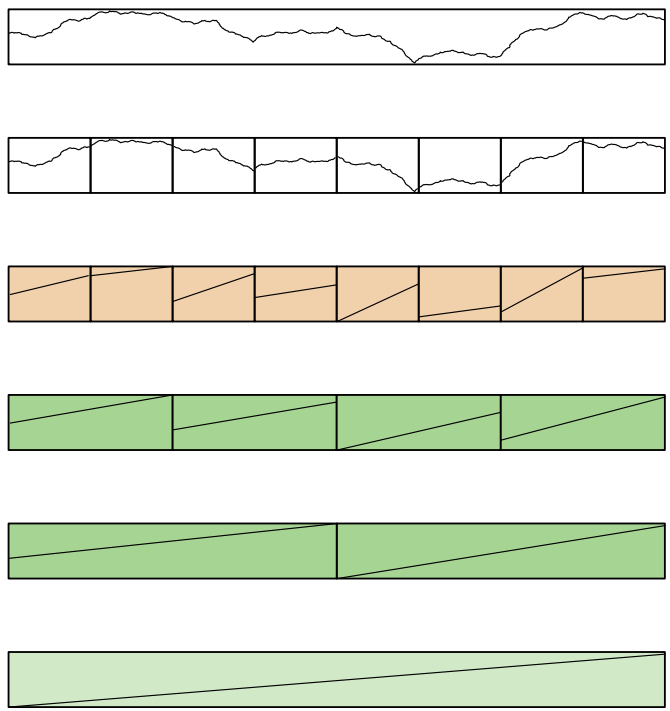

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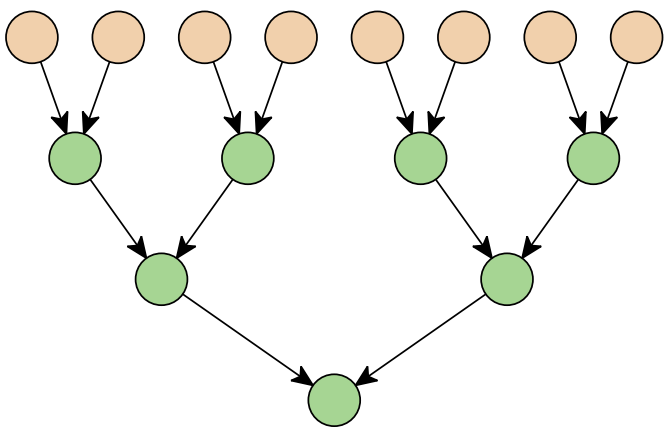

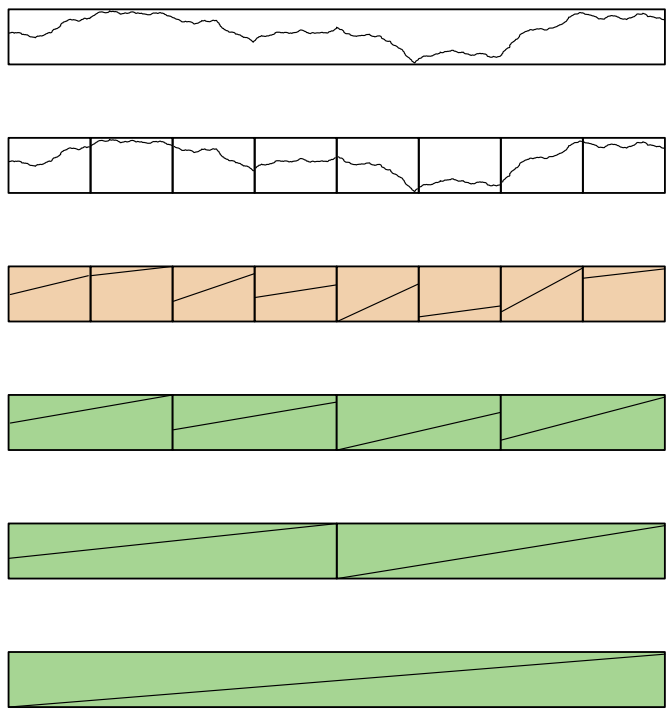

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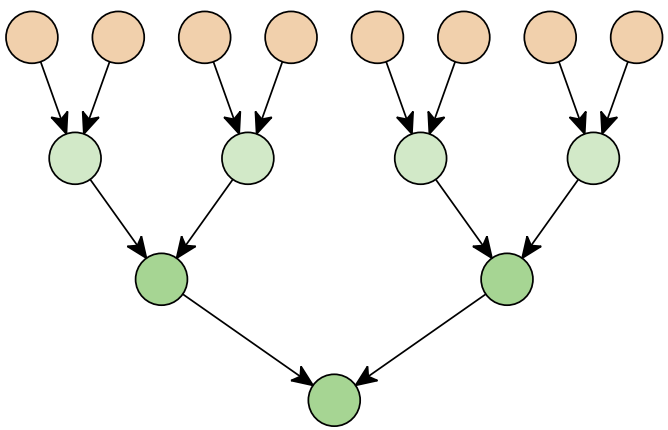

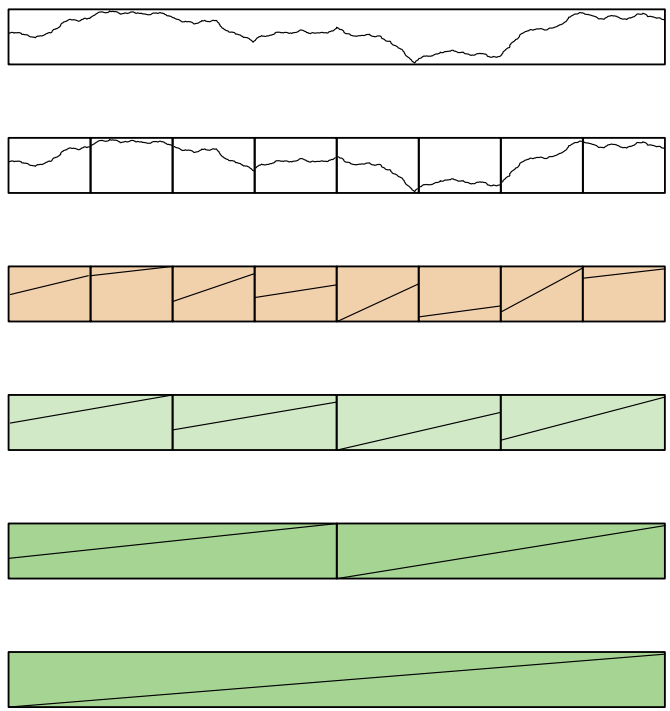

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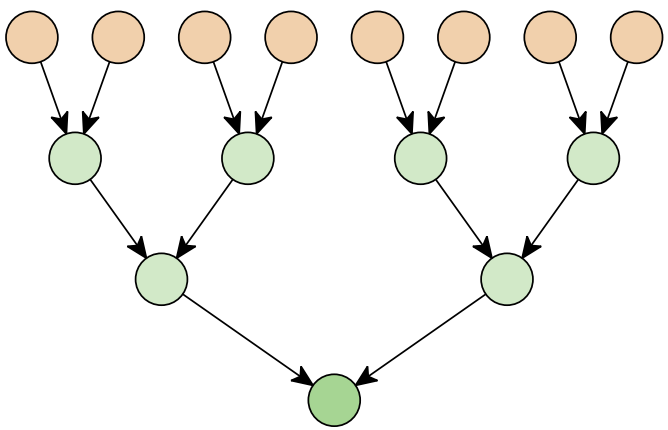

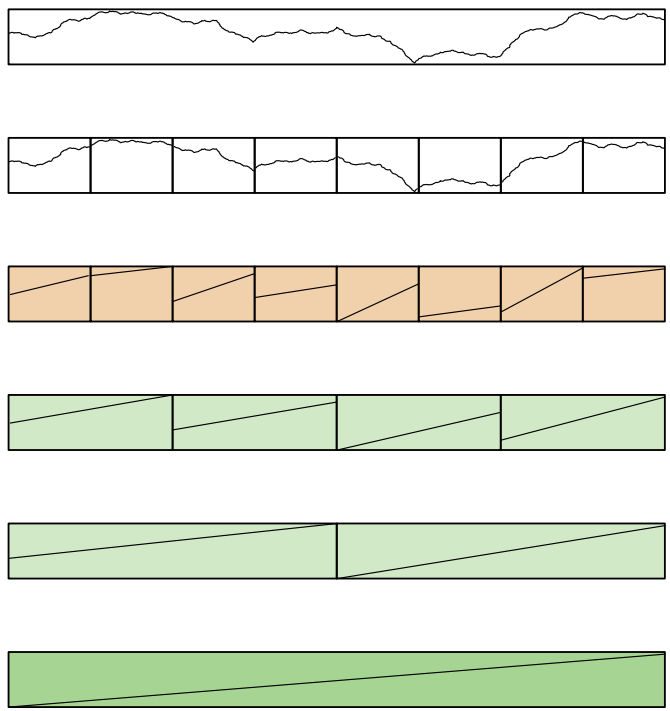

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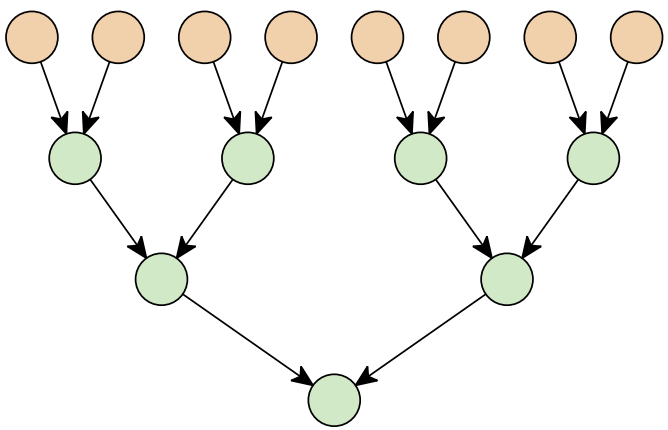
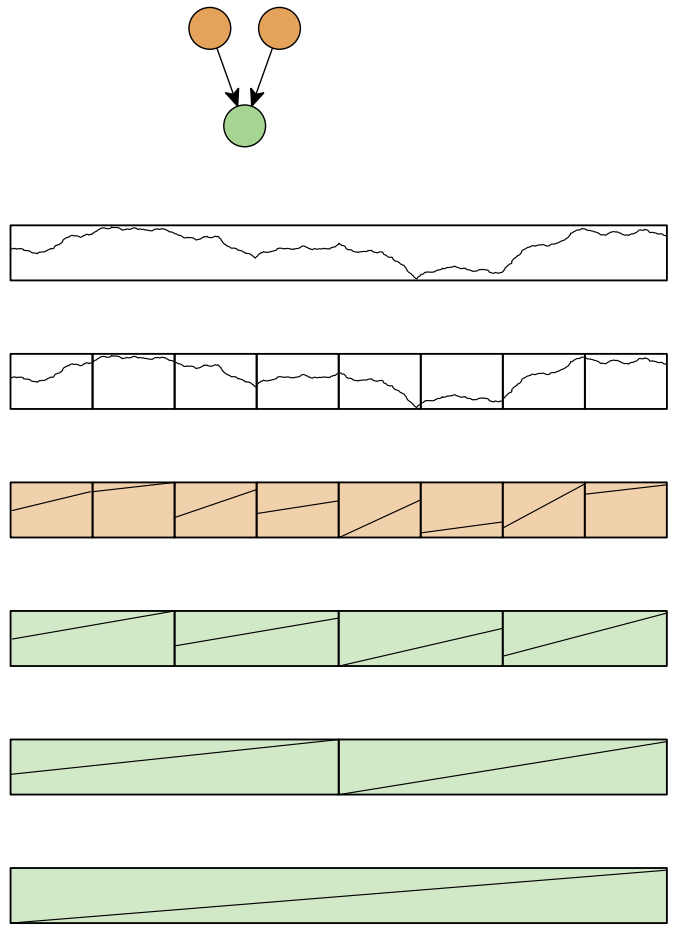


Provided

- 1 level tree (*src/merge-*.graphml*)



Write Task Code

Presort already provided

- Reuses sort code of part 1 (*src/sort.cpp*)

Write Task Code

Presort already provided

- Reuses sort code of part 1 (*src/sort.cpp*)
- Implement merge task

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Classic: all data available

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1  Function merge(l, ls, r, rs, o)
2      lc ← rc ← 0;
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4          if l[lc] < r[rc] then
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Pipelined: only a portion of data at a time

- Merge items as in classic merge (lines 3 to 10)
  - But output channel may be full

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See compendium and skeleton for operations on channels (peek, pop, push, empty) and tasks (killed).

Describe target platform

Platform description: *src/platform*.dat*

```
# Number of cores
param p := 1;

# Frequency levels
set F := 1200 1400 1500 1600 1700 1900 2000 2100
         2200 2300 2500 2700 2900 3000 3200 3300 3500;
param Funit := 1000000;
param Fin := 1;
set Fi[1] := 1;
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Describe target platform

Platform description: *src/platform*.dat*

- Number of cores: *p*

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Describe target platform

Platform description: *src/platform*.dat*

- Number of cores: *p*
- DVFS: unused this lab

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Describe target platform

Platform description: *src/platform*.dat*

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Provided:
1 core platform description,
See below

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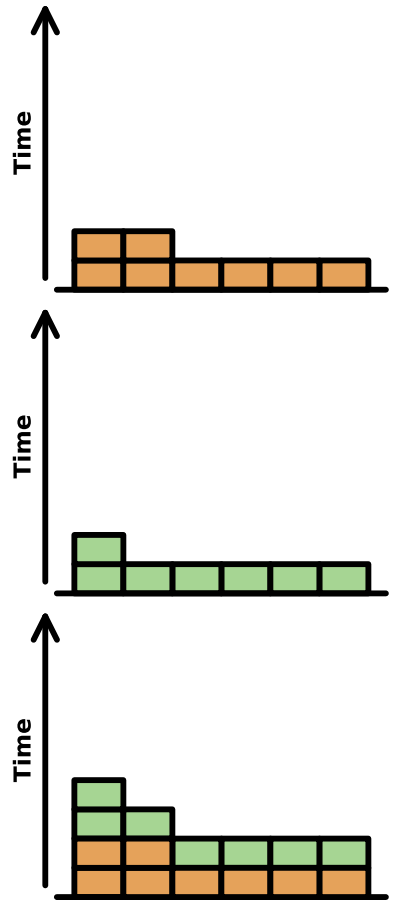
Define schedule

Actual parallel speedup

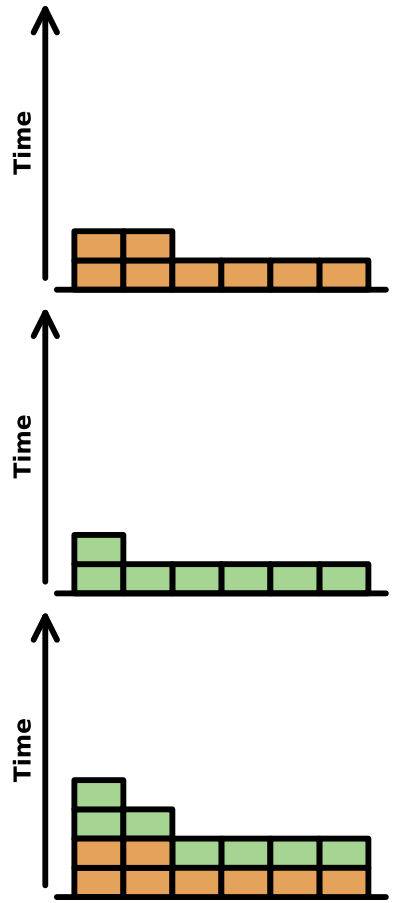
- Spread load to cores



Define schedule

Actual parallel speedup

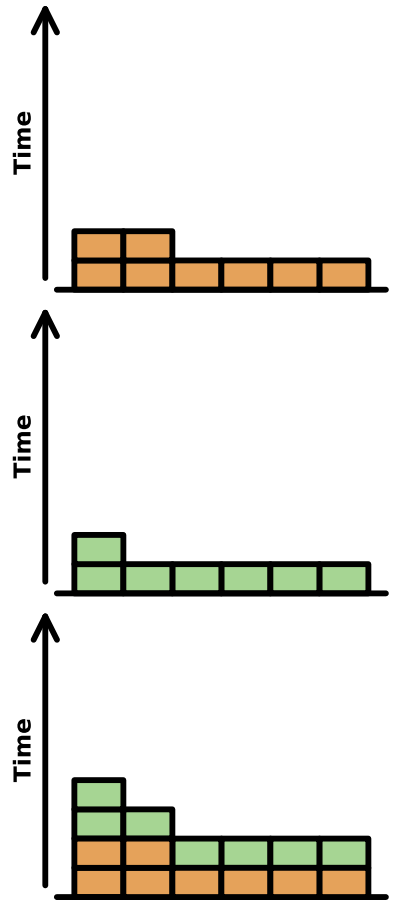
- Spread load to cores
- Streaming vs Non-Streaming tasks
  - Don’t run at the same time



Define schedule

Actual parallel speedup

- Spread load to cores
- Streaming vs Non-Streaming tasks
  - Don't run at the same time
  - Presort: non-streaming
  - Merge: streaming



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Actual parallel speedup

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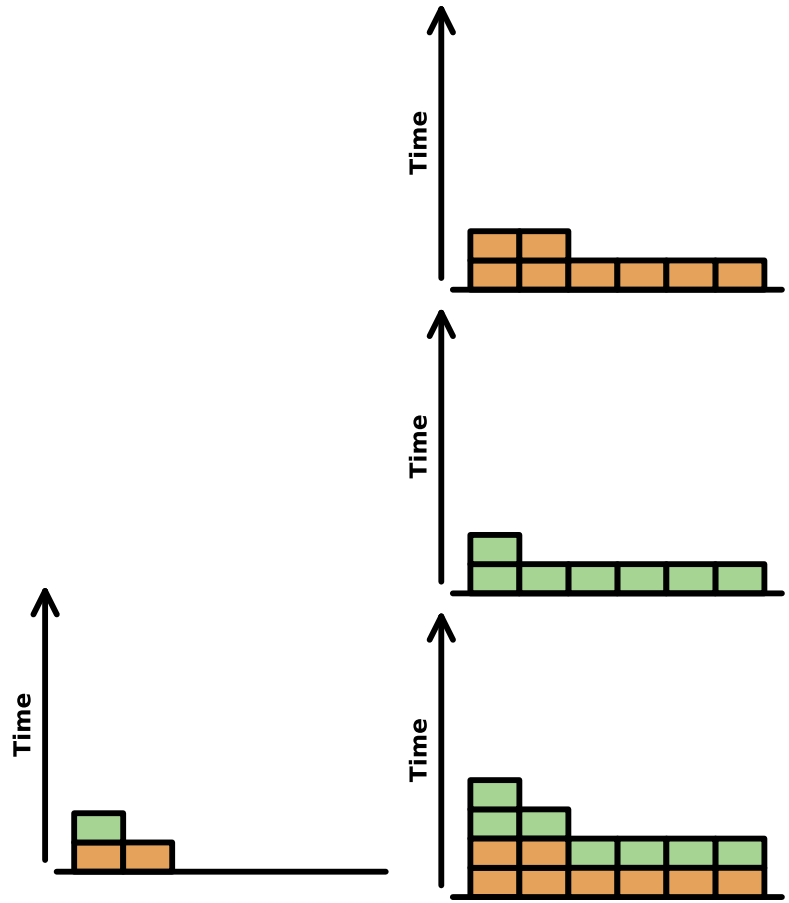


Example:

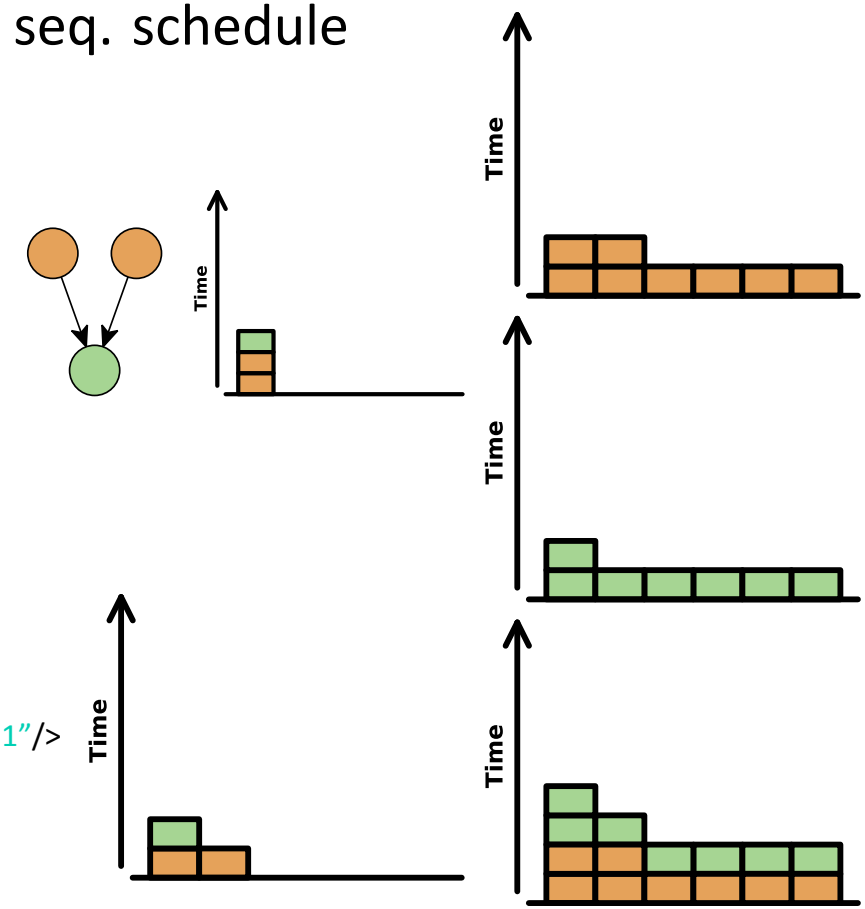
```
<?xml version="1.0" encoding="UTF-8"?>
<schedule name="nicme26" appname="pipelined_merge">
 <core coreid="1">
  <task name="leaf_1" start="0" frequency="3500" width="1" workload="1"/>
  <task name="root" start="2.85e-7" frequency="3500" width="1" workload="1"/>
 </core>
 <core coreid="2">
  <task name="leaf_2" start="0" frequency="3500" width="1" workload="1"/>
 </core>
</schedule>
```

Define schedule

Actual parallel speedup

- Spread load to cores
- Streaming vs Non-Streaming tasks
  - Don't run at the same time
  - Presort: non-streaming
  - Merge: streaming

Provided: 1-level seq. schedule



Example:

```
<?xml version="1.0" encoding="UTF-8"?>
<schedule name="nicme26" appname="pipelined_merge">
 <core coreid="1">
  <task name="leaf_1" start="0" frequency="3500" width="1" workload="1"/>
  <task name="root" start="2.85e-7" frequency="3500" width="1" workload="1"/>
 </core>
 <core coreid="2">
  <task name="leaf_2" start="0" frequency="3500" width="1" workload="1"/>
 </core>
</schedule>
```

Compile & Test Application

Compile for debugging

- Task graph: *src/merge.graphml*
- Platform description: *src/platform.dat*
- Schedule: generated by LPT in *src/merge.schedule.xml*

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Testing

- Generate inputs with *src/generate*
- Use *dump* to inspect input data file
- Test correctness of *src/drake-sort* and *src/parallel-sort*
- Use *backtrace* from crashed programs' outputs to locate errors

Measure Performance

Skeleton compiles variants for 1 to 6 cores

- Handwritten parallel sort: *NB_THREADS* preprocessor symbol in *src/sort.cpp*.

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- Drake-based parallel sort for *x* cores
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  - Platform description: *src/merge-x.graphml*
  - Schedule: *src/schedule-x.xml*

Measure Performance

Skeleton compiles variants for 1 to 6 cores

- Handwritten parallel sort: *NB_THREADS* preprocessor symbol in *src/sort.cpp*.
- Drake-based parallel sort for *x* cores
  - Task graph: *src/merge-x.graphml*
  - Platform description: *src/merge-x.graphml*
  - Schedule: *src/schedule-x.xml*

Begin process:

- Compilation: *freja compile --log compile.log*
  - Takes a while with deep merge trees
  - See compilation details in *compile.log*

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- Experiment: *freja run <name> --log <name>.log*
  - Remove directory <name> before running again
- Plotting: *./drawplots*

Lab 3: Inspiration

- Quick sort: `http://www.youtube.com/watch?v=ywWBy6J5gz8`
- Merge sort: `http://www.youtube.com/watch?v=XaqR3G_NVoo`
- Select sort: `http://www.youtube.com/watch?v=Ns4TPTC8whw`
- Bubble sort: `http://www.youtube.com/watch?v=lyZQPjUT5B4`
- Shell sort: `http://www.youtube.com/watch?v=CmPA7zE8mx0`
- Insert sort: `http://www.youtube.com/watch?v=ROalU37913U`
- Bogo sort: `http://en.wikipedia.org/wiki/Bogosort`
- Ineffective sorting: `http://xkcd.com/1185/`

Lab 3: Anti-inspiration

Figure: Nobody will pass these algorithms, even parallelized. Creative Commons Attribution-NonCommercial 2.5 License http://xkcd.com/1185/

Optional: High performance parallel programming challenge 2015

- Design and implement the fastest algorithms
- One round for CPUs and another on GPUS
- Participation of both rounds and on time submission is mandatory to win the prize
- Participation to the challenge at all is optional
- Prize: cinema tickets and certificate

Suggested planning

- Week 45: Lecture – Shared memory and non-blocking synchronization
- Week 46: Lab 1 – Load balancing
  - Soft deadline: Friday 11/13
- Week 46-47: Lecture – Parallel sorting algorithms
- Week 47: Lab 2 – Non-blocking synchronization
  - Soft deadline: Friday 11/20
- Week 48: Lab 3 – Parallel sorting
  - Soft deadline: Friday 11/27
- Thursday 12/18: Deadline for the CPU and GPU parallel sorting challenge
- Friday 12/19: Challenge prize ceremony and hard deadline for labs

Final remarks

- **Do your homework before the lab session**
- KISS: Keep It Simple and Stupid
  - Donald Knuth: “Premature optimization is the root of all evil”
  - Simple code often fast and good base for later optimizations
  - Start with the most possibly simple sequential code until it works
  - Then, parallelize it the most simple way you can think of, discard optimizations for now
  - Only then, improve your code: running in-place, data locality issues, thread pools, etc.
  - Read `http://en.wikipedia.org/wiki/Program_optimization`, section ”when to optimize”
- Modify lab skeletons at will!
  The exercice consists in the demonstration of understanding, not just the implementation of an expected outcome.

Final remarks

- Tight deadline
  - Implement your lab before the lab sessions
  - Use the lab session to run measurements and demonstrate your work
  - Contact your lab assistant to get help
- Help each other: find inspiration with discussions between groups
  - But code and explain solutions yourself
- **Do your homework before the lab session**
- Find me in my office 3B:488
- Introductory practice exercises on C, pthreads and measurements
  - `http://www.ida.liu.se/~nicme26/tddd56.en.shtml`, labs 0a, 0b
  - `http://www.ida.liu.se/~nicme26/measuring.en.shtml`
- Google is your friend (or claims to be so)
- A lot of useful information in the (long) lab compendium. Read them!

End of lesson 1

Next lesson: theory exercises

Thank you for your attention