Scheduling parallel program with Work stealing

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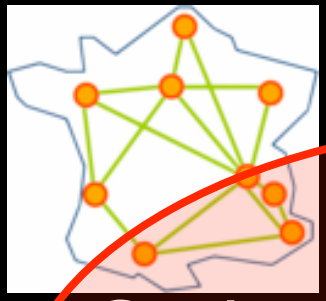
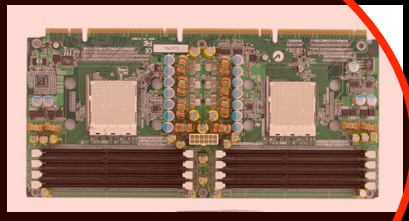
Seminar at UFRGS, Porto Alegre, Brazil

Moais Positioning



Grid

Cluster

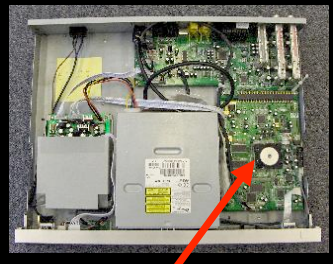


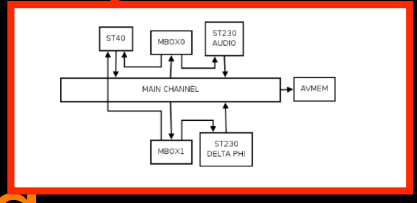
Multicore

KAAPI

GPU

MPSoC





To mutually adapt application and scheduling

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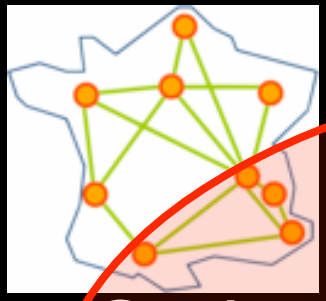

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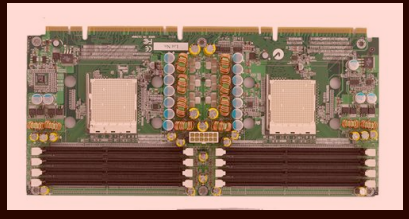

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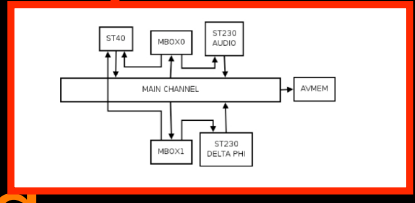


KAAPI

To mutually adapt application and scheduling

MOAIS group

- Funded by INRIA, CNRS, UJF, INPG
- Part of LIG (Laboratoire d'Informatique de Grenoble)
  - http://moais.imag.fr
- Jean-Louis Roch: project Leader
- 10 researchers
- 18 PhD students

Research actions

- Scheduling [Denis Trystram]
  - multi-objectif criteria, malleable and moldable model
- Parallel Algorithms [Jean-Louis Roch]
  - adaptive algorithms
- Virtual Reality [Bruno Raffin]
  - interactive simulation
- Runtime for HPC [Thierry Gautier]
  - grid and cluster, multi-processor

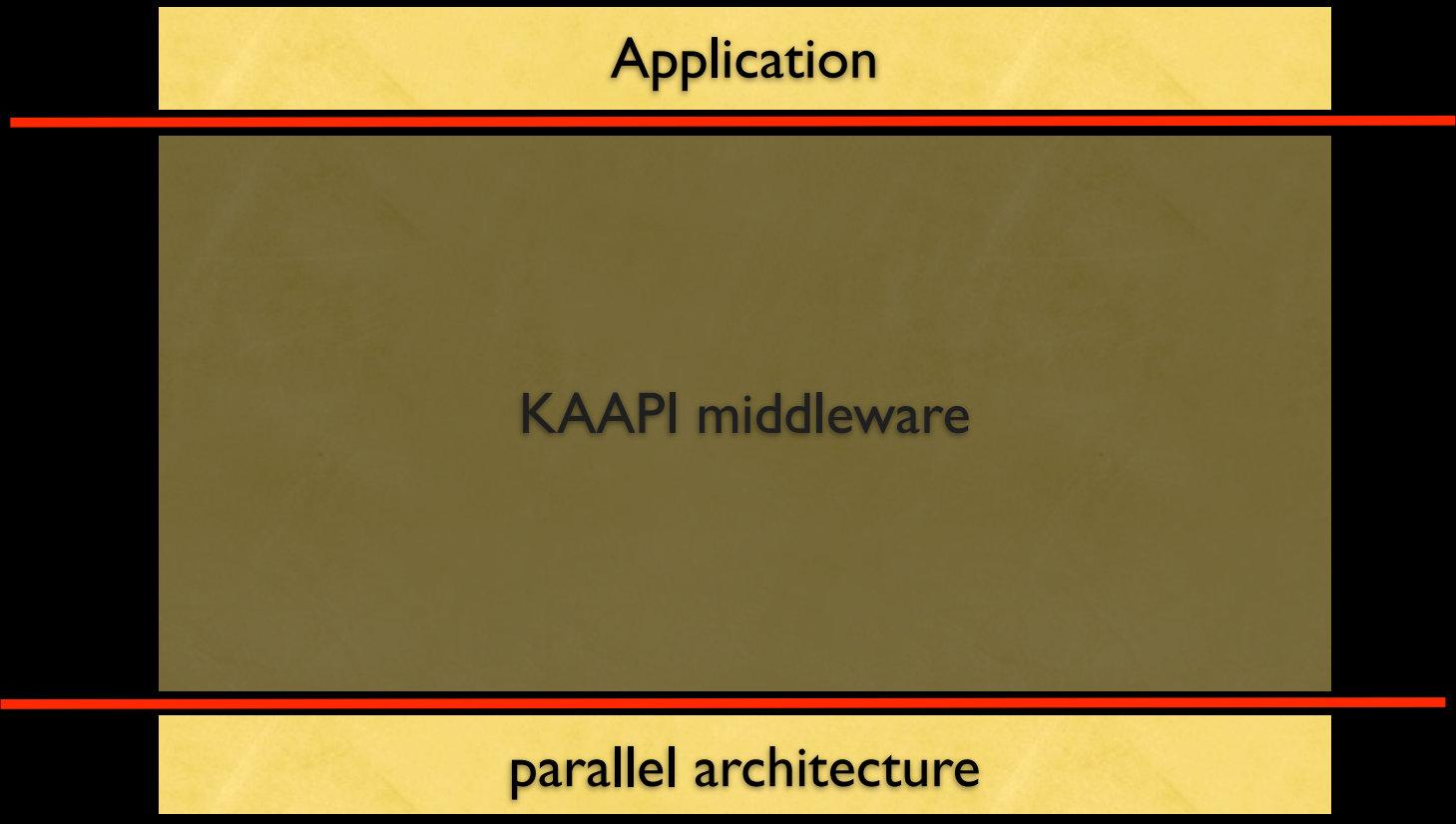
Outline

- Athapascan / Kaapi a software stack
- Foundation of work stealing
- Controls of the overheads
- Experiments with STL algorithms

Goal

- Write once, run anywhere... with guaranteed performance
- Problem: heterogeneity
  - variations of the environment (#cores, speed, failure...)
  - irregular computation

KAAPI Overview



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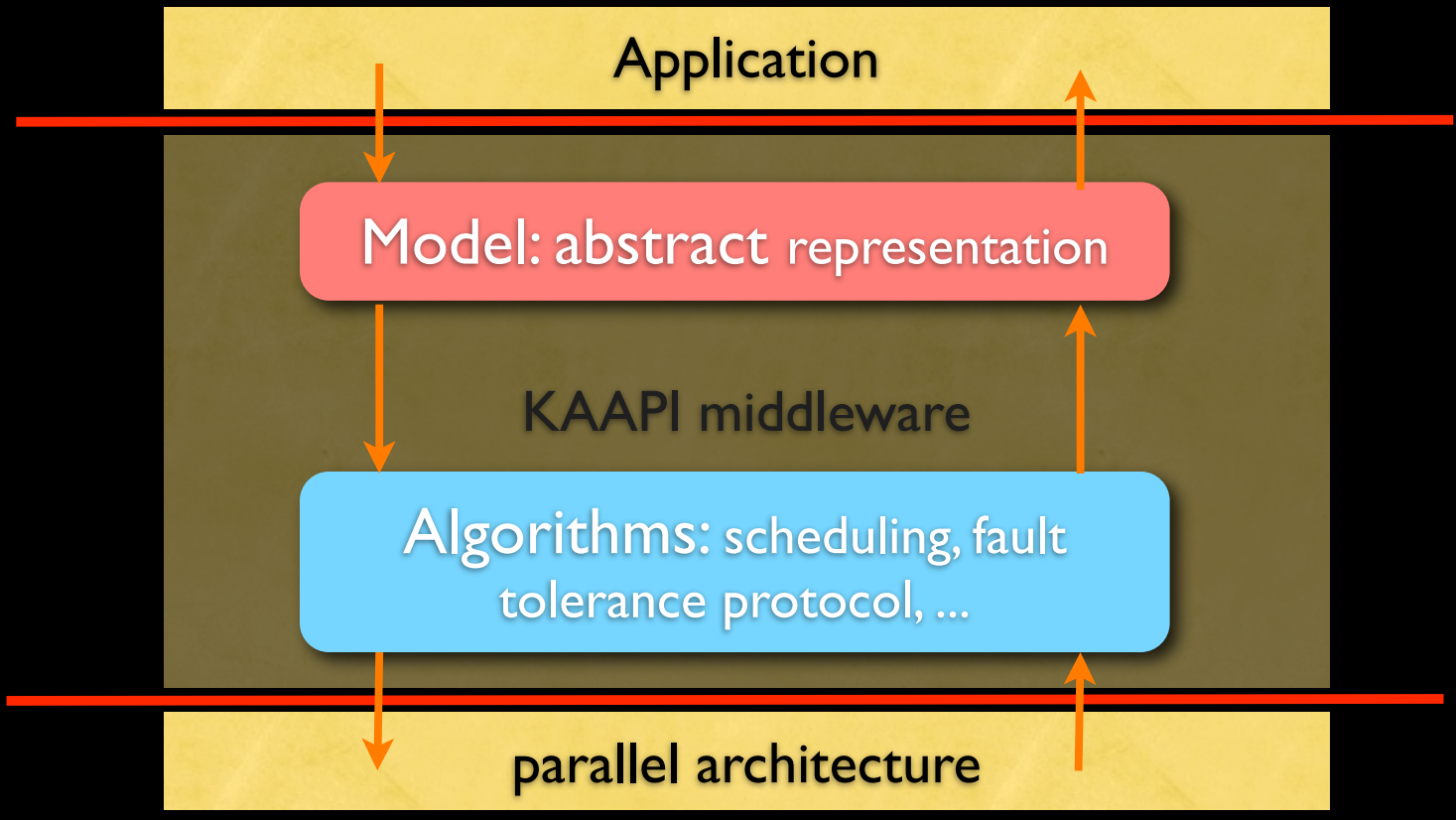

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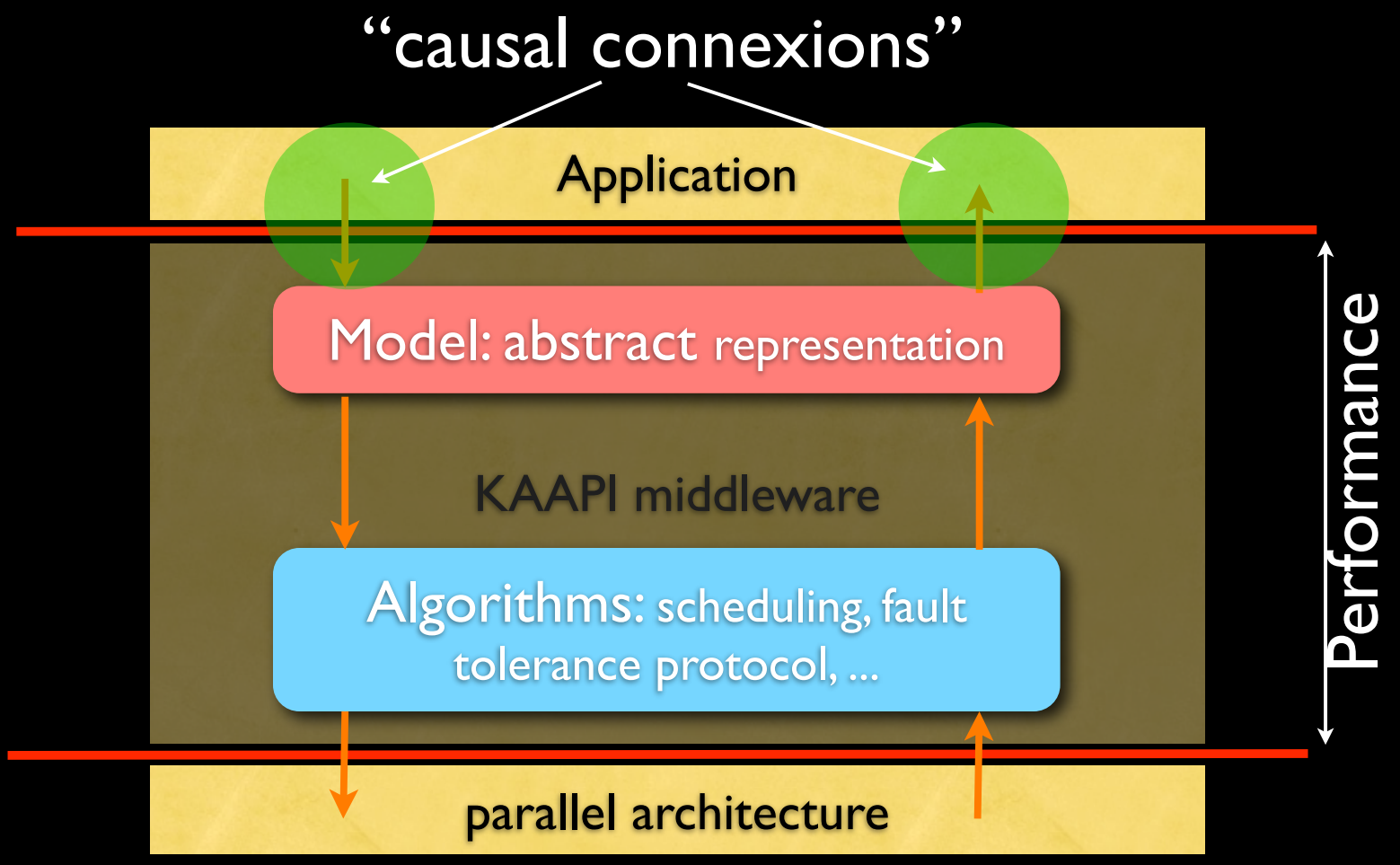

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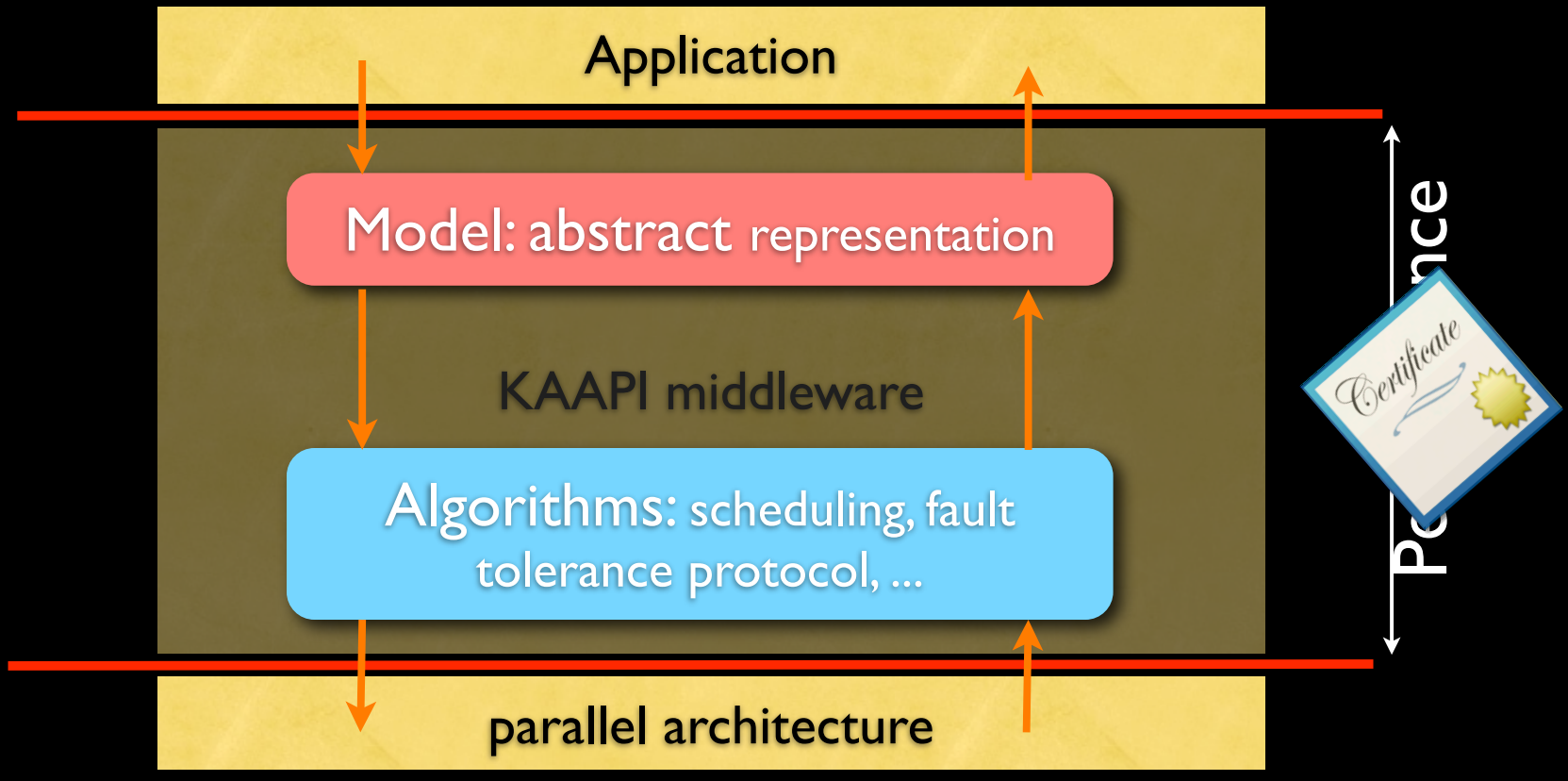

API: Athapascan

- Global address space
  - Creation of objects in a global address space with ‘shared’ keyword
- Task = function call
  - Creation with ‘Fork’ keyword (≠ unix fork) ~ Cilk spawn
  - Tasks only communicate through shared objects
  - Task declares access mode (read, write, concurrent write, exclusive) to shared objects
- Automatic scheduling
  - Work stealing or graph partitioning

➡ ‘Sequential’ semantics

- C++ library, not a language extension
  - C language extension + compiler was prototyped

Fibonacci example

```
struct Fibonacci {
  void operator()( int n, a1::Shared_w<int> result )
  {
     if (n < 2) result.write( n );
     else {
        a1::Shared<int> subresult1;
        a1::Shared<int> subresult2;
        a1::Fork<Fibonacci>()(n-1, subresult1);
        a1::Fork<Fibonacci>()(n-2, subresult2);
        a1::Fork<Sum>()(result, subresult1, subresult2);
     }
  }
};

struct Sum {
  void operator()(   a1::Shared_w<int> result,
                     a1::Shared_r<int> sr1,
                     a1::Shared_r<int> sr2 )
  { result.write( sr1.read() + sr2.read() ); }
}
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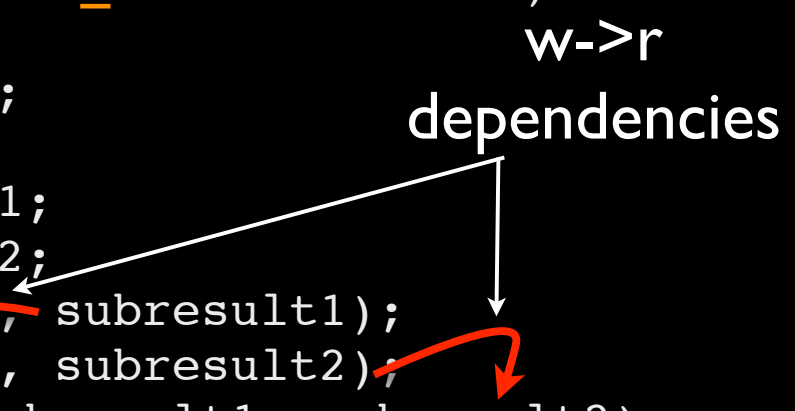

Semantics & C++ Elision

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```

Semantics & C++ Elision

```
struct Fibonacci {
  void operator()( int n,                    int& result )
  {
     if (n < 2) result =       n   ;
     else {
                    int   subresult1;
                    int   subresult2;
                  Fibonacci ()(n-1, subresult1);
                  Fibonacci ()(n-2, subresult2);
                  Sum ()(result, subresult1, subresult2);
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};

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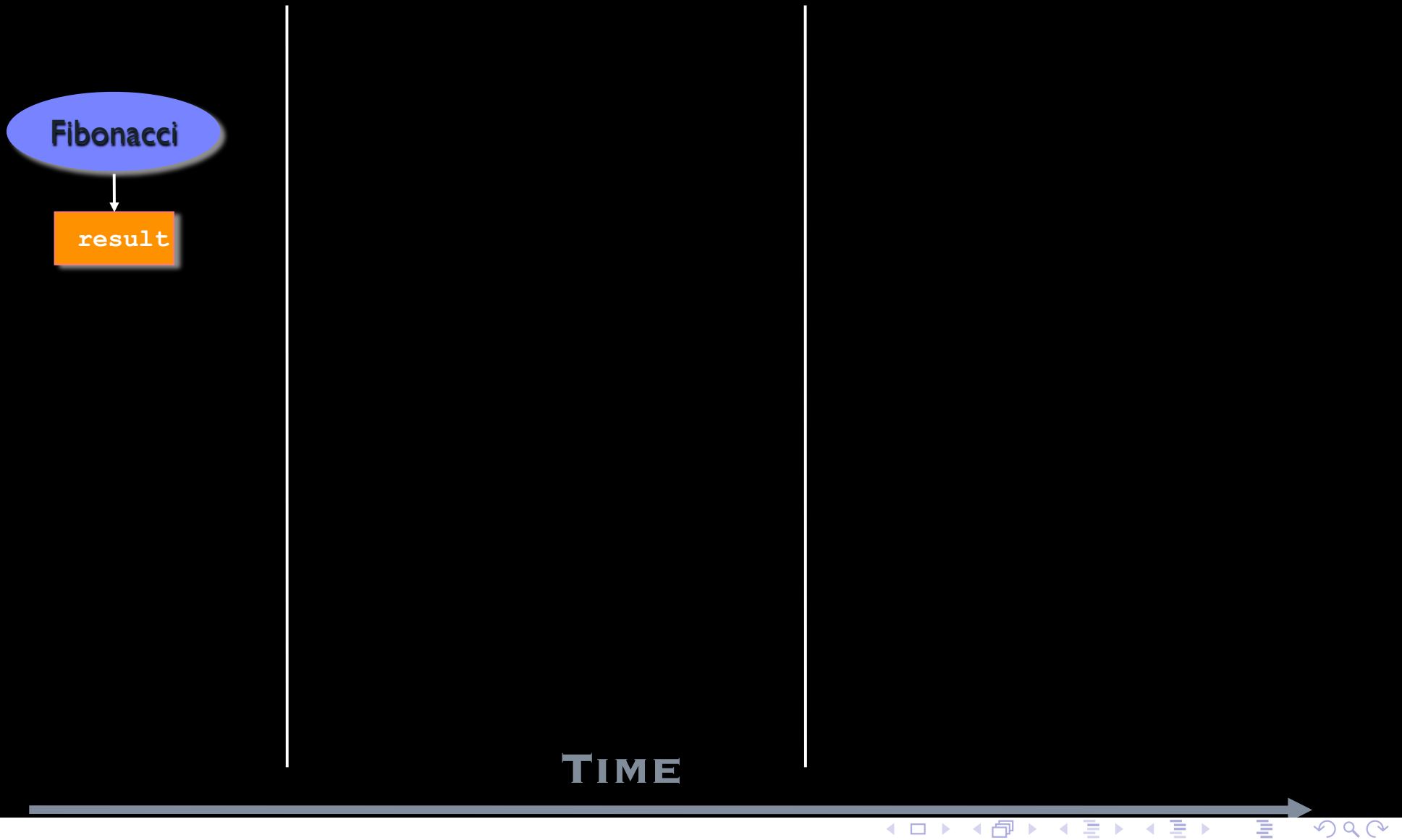
```

Online construction



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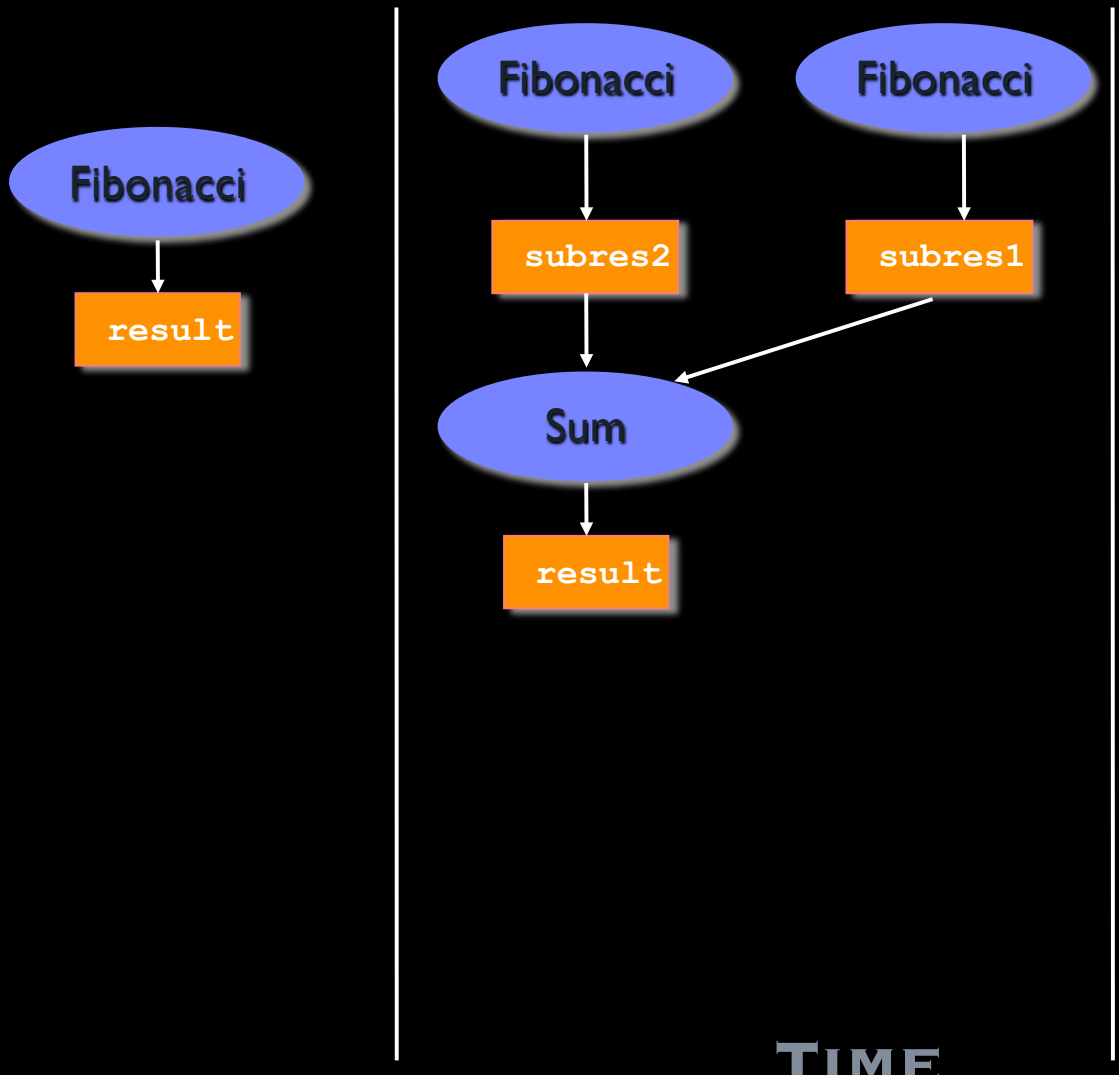

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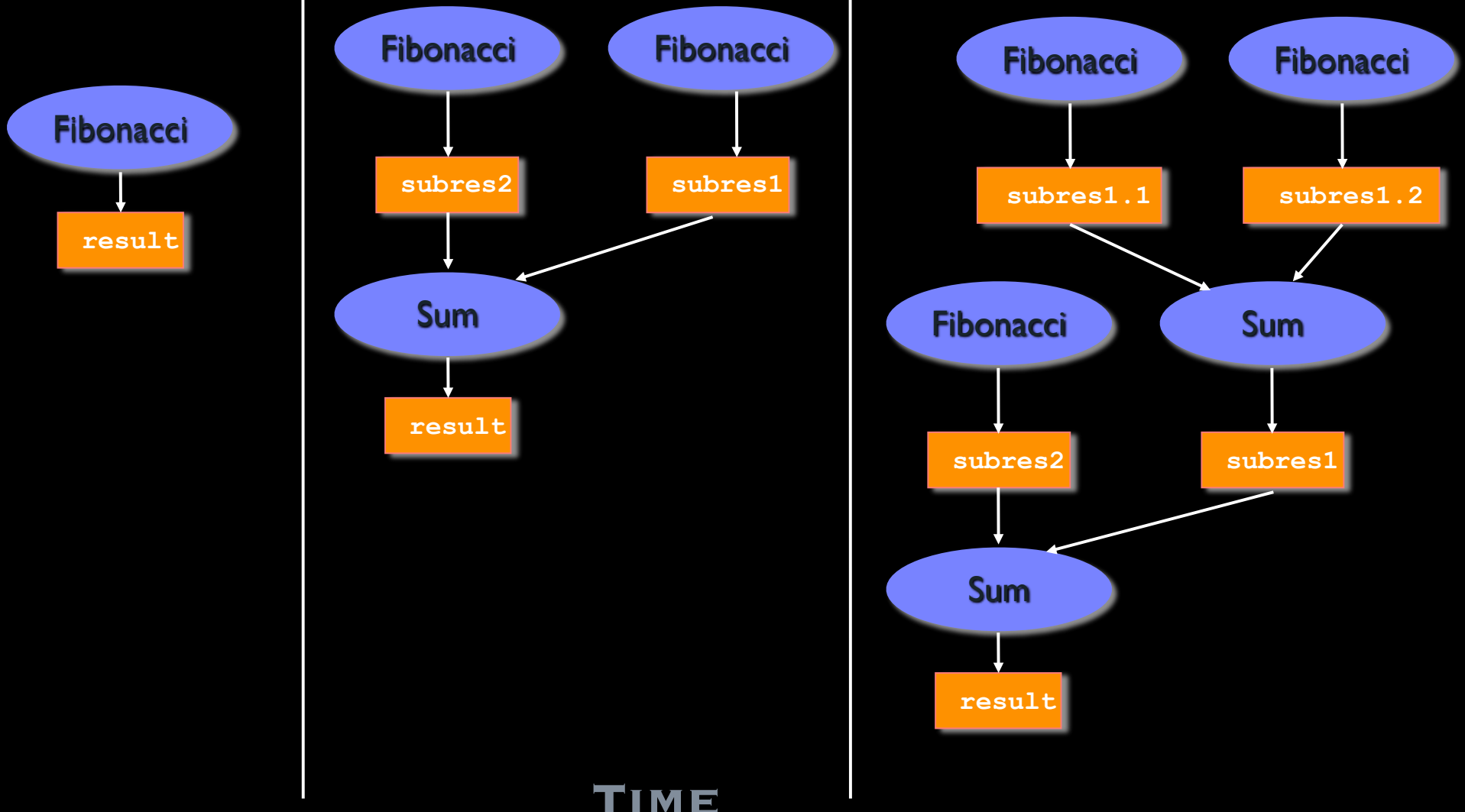

Data Flow Graph Interests

- One abstract representation for
  - Scheduling
    - data flow graph ⇒ precedences graph ⇒ dependences graph
      - classical numerical kernel ⇒ partitioning the dependences graph
  - Explicit data transfer
    - data to be transfered is explicit in the data flow graph
      - automatic overlapping communication by computation
  - Original Fault Tolerant Protocols
    - TIC [IET05, Europar05, TDSC09]
      - coupling scheduling by work stealing with abstract representation
    - CCK [TSI07, MCO08]
      - coordinated checkpointing with partial restart after failure
  - Sabotage Tolerance [PDP09]
    - dynamically adapt the execution to sabotage
- Drawback: complexity to manage it

Stack management

- Stack based allocation
  - Tasks and accesses to shared data are pushed in a stack
    - close to the management of the C function call stack
  - O(1) allocation time
  - O(#parameters) initialization time

```
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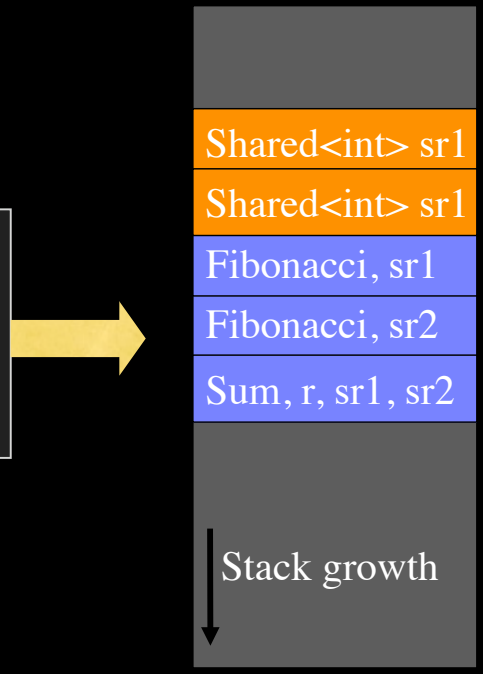
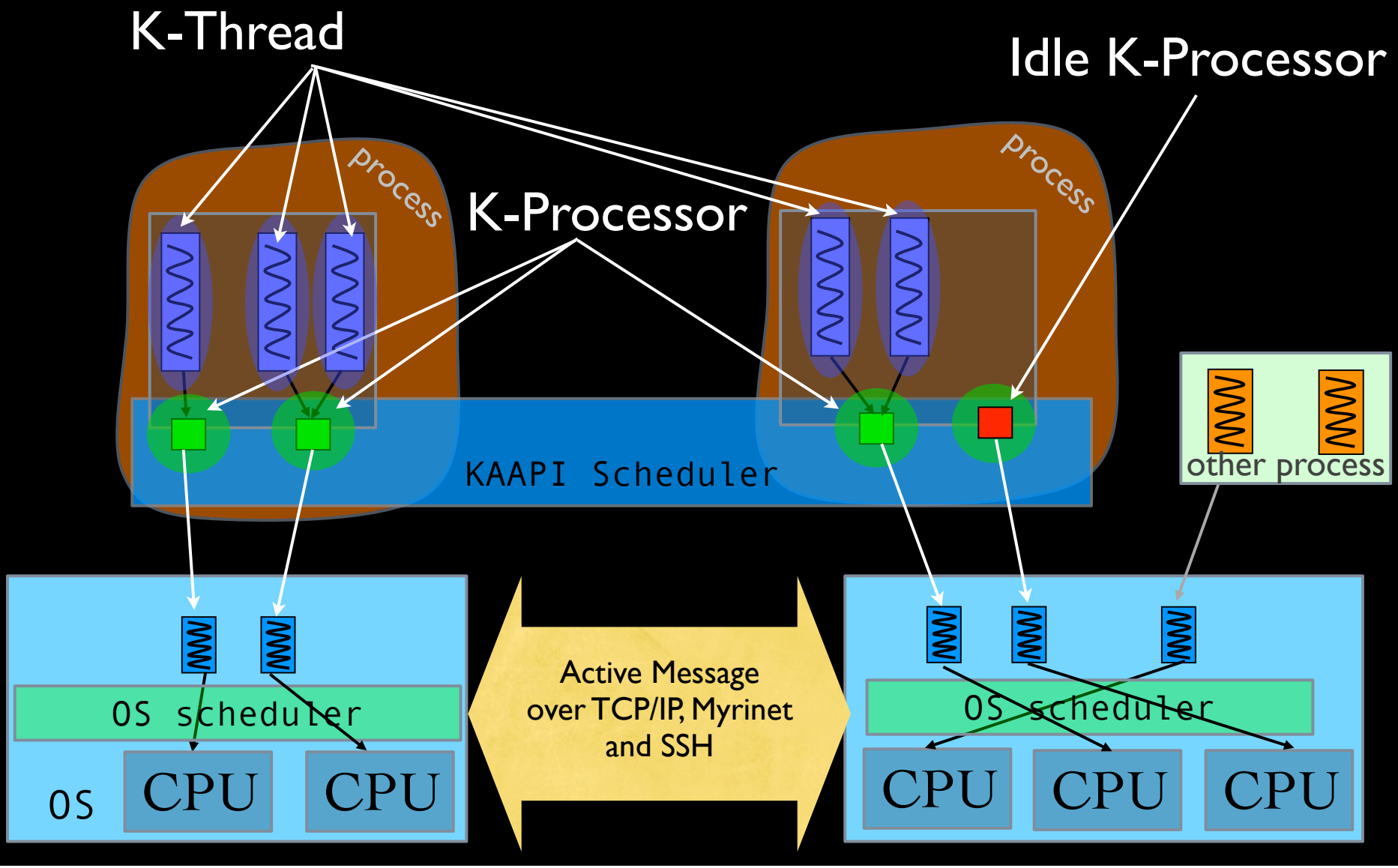


Execution model

- A (dynamic) set of UNIX processes
  - communication by active message
  - Each process is multithreaded
  - The root process forks the main task
- Threads inside processes are either
  - Performing work
    - excute tasks
  - idle and participate to scheduling
    - then it try to steal work (task) from other threads (work-stealing algorithm)

2 Level Scheduling



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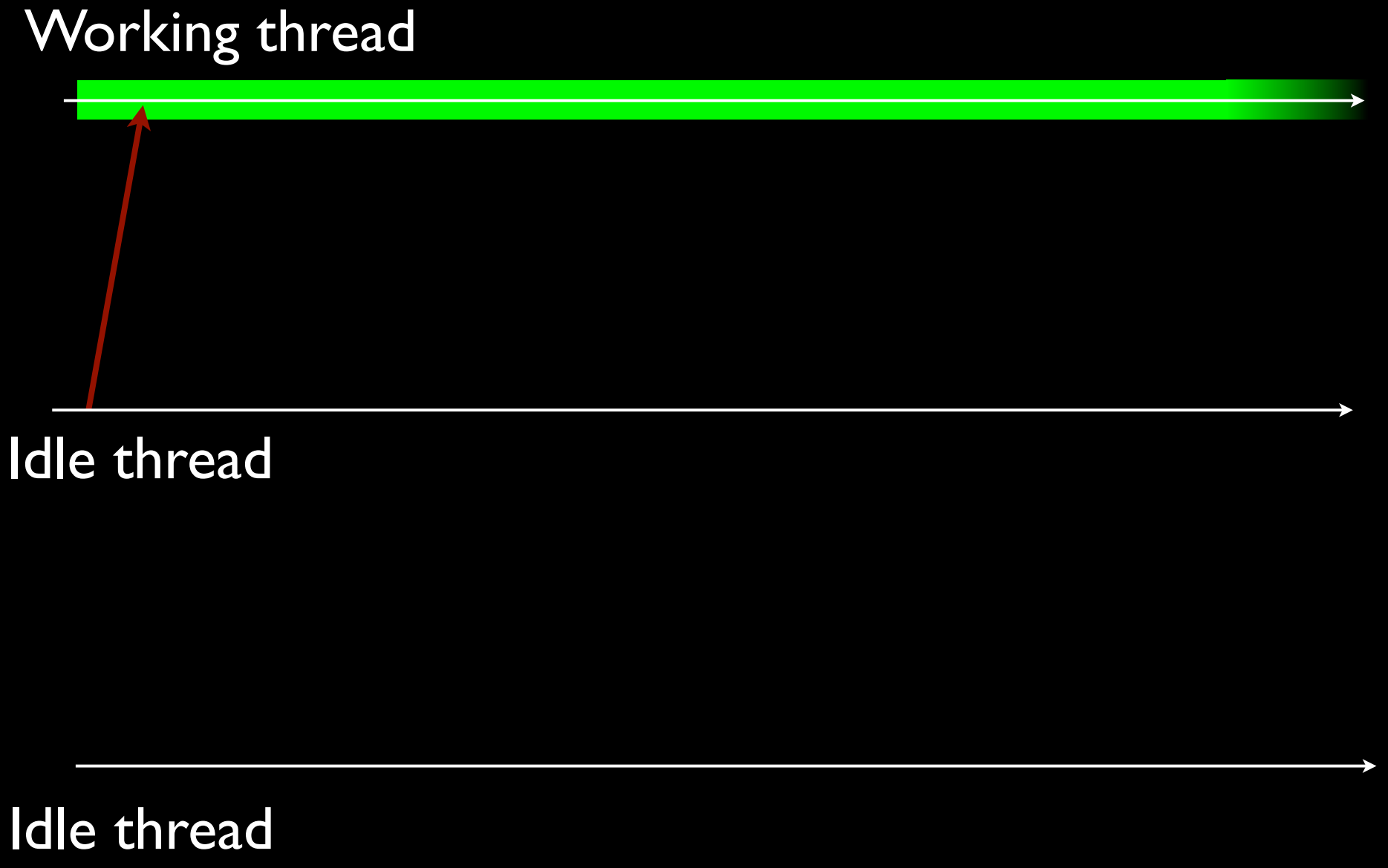
Principle of work stealing



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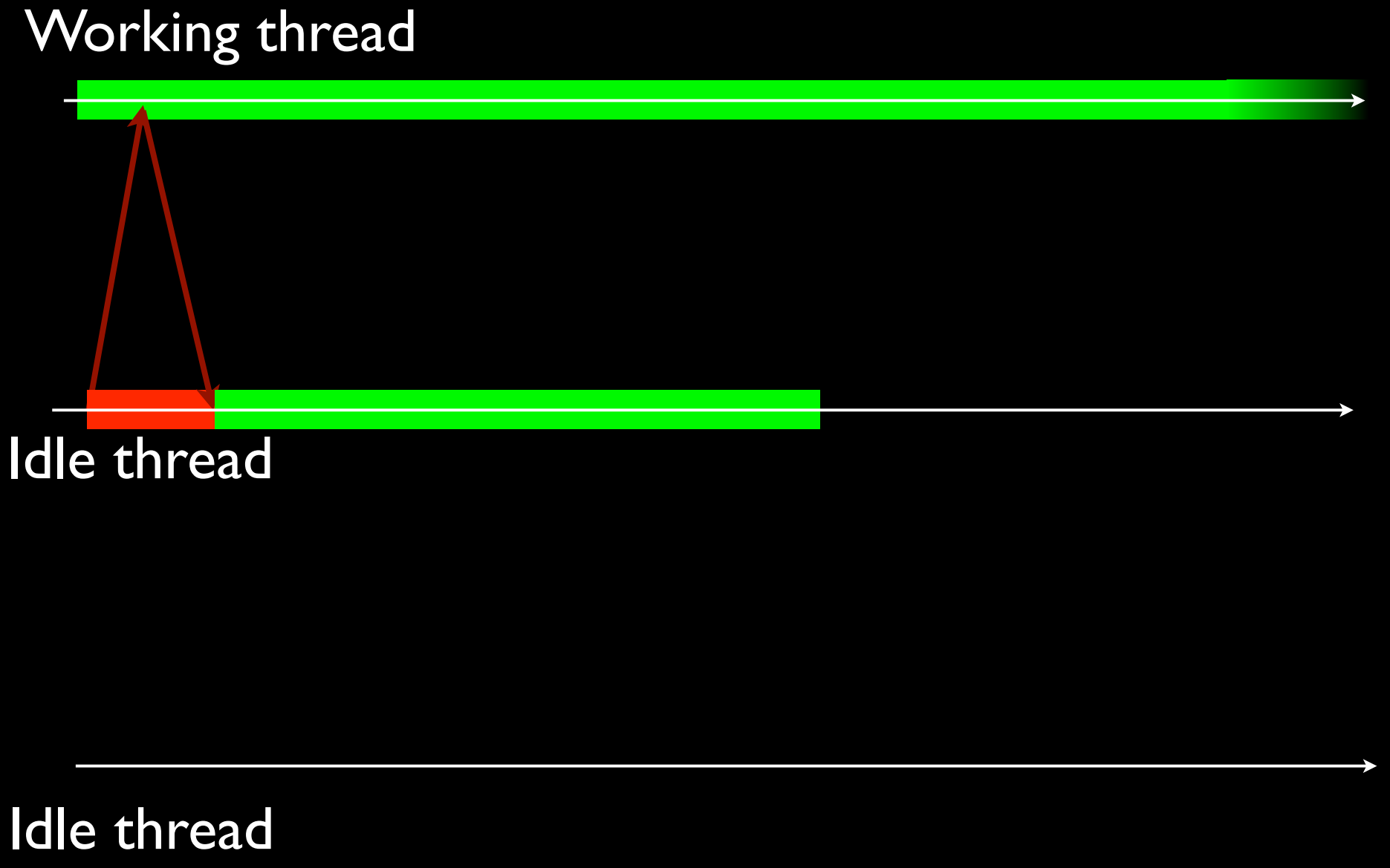

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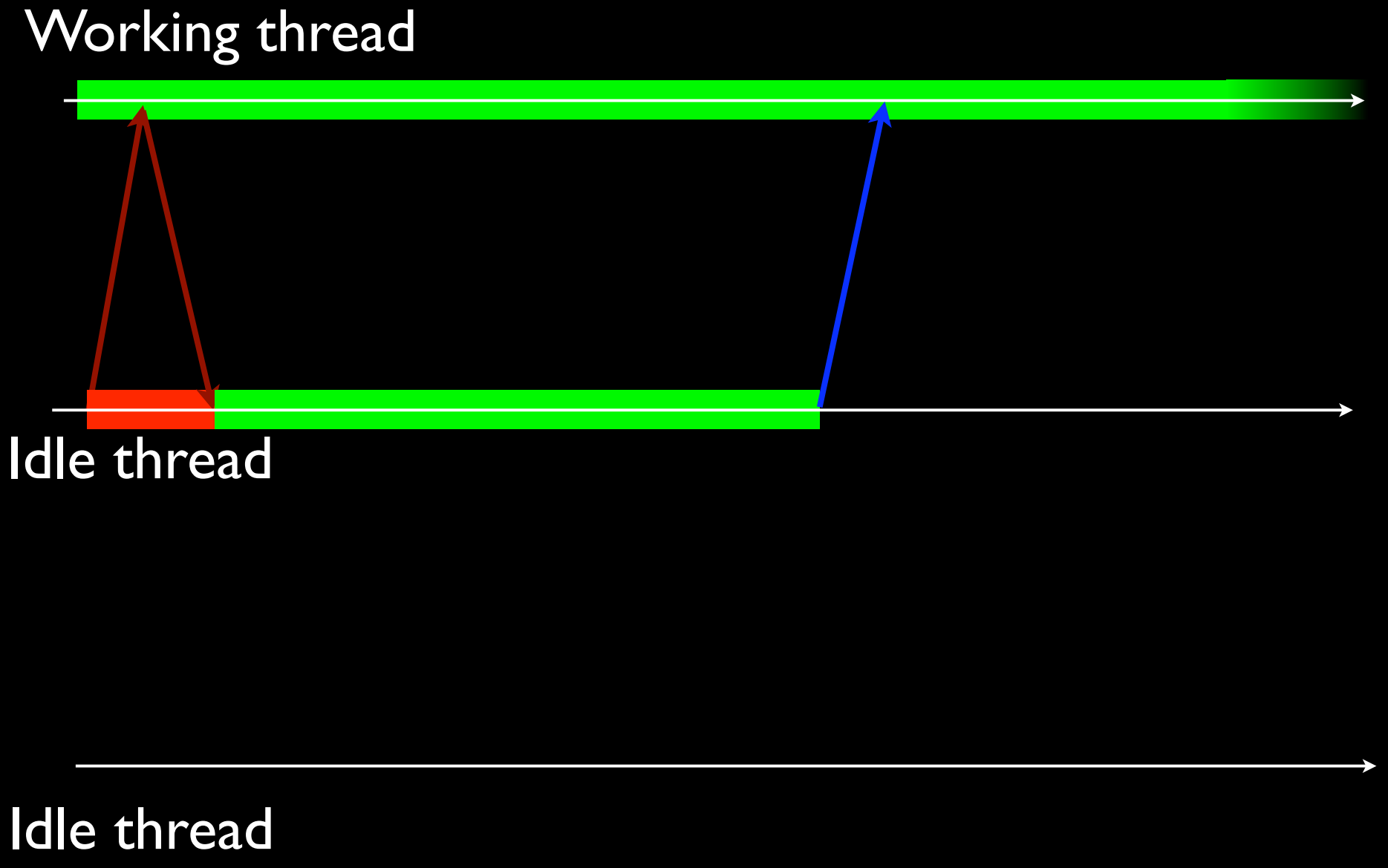

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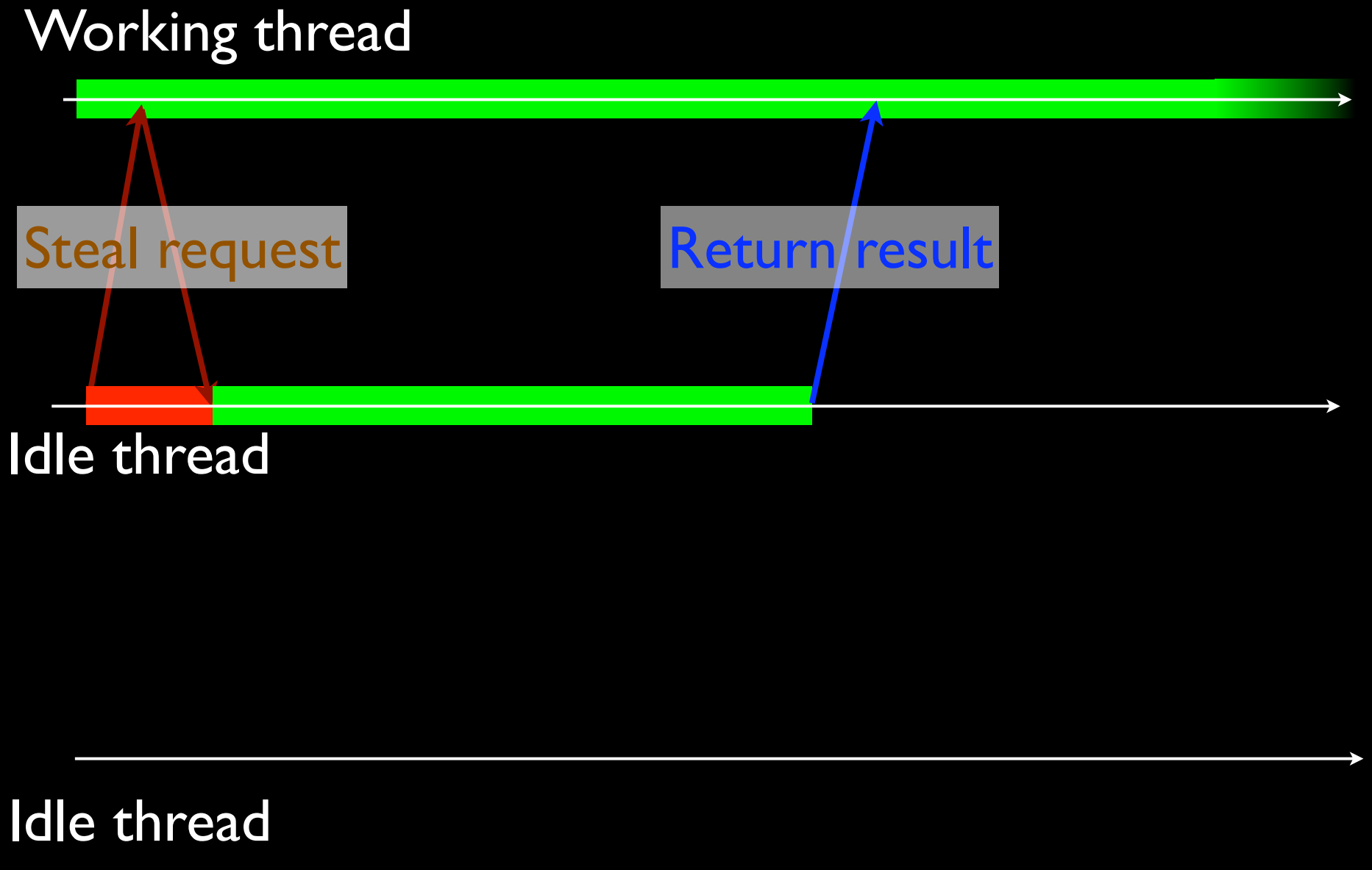

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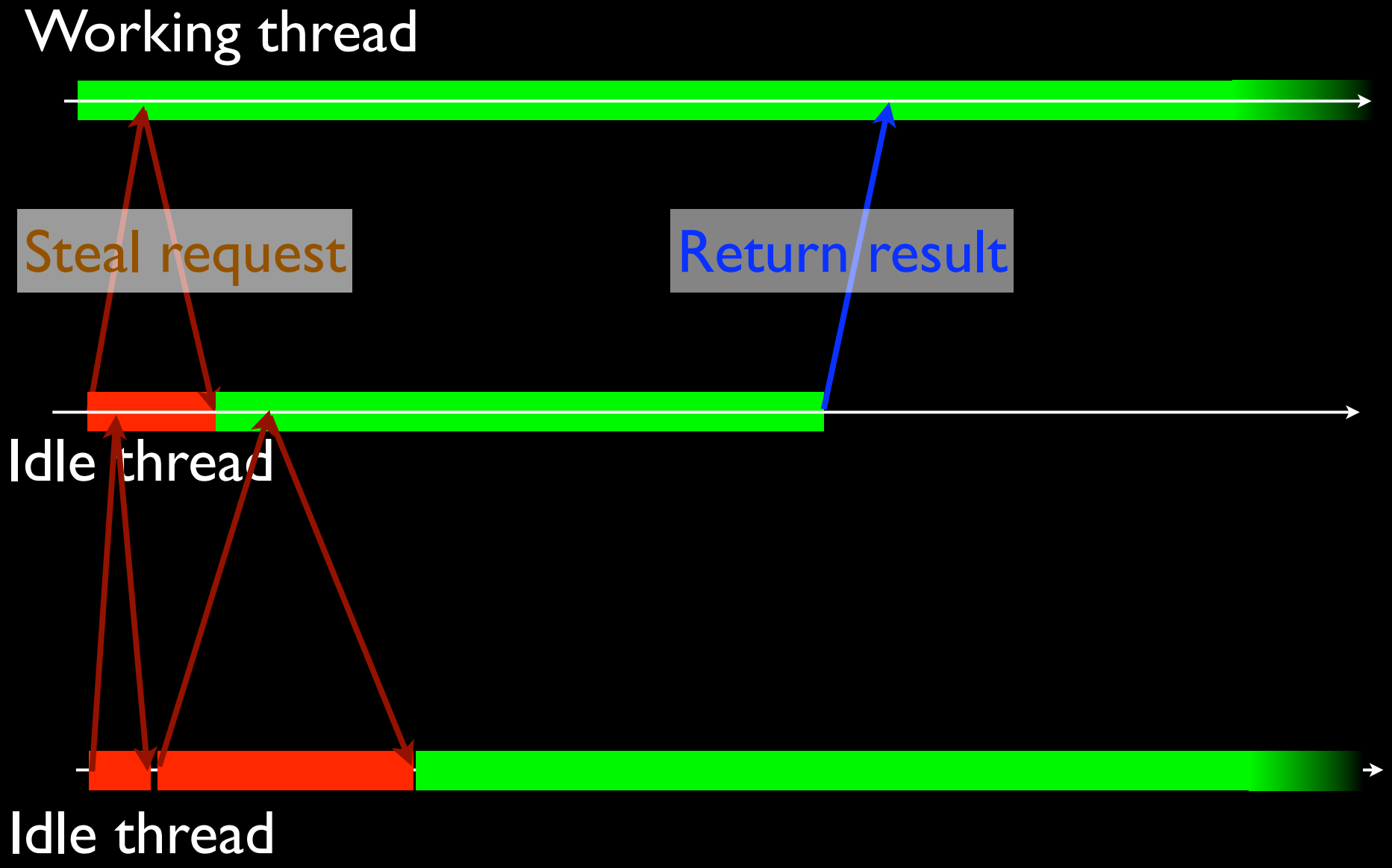

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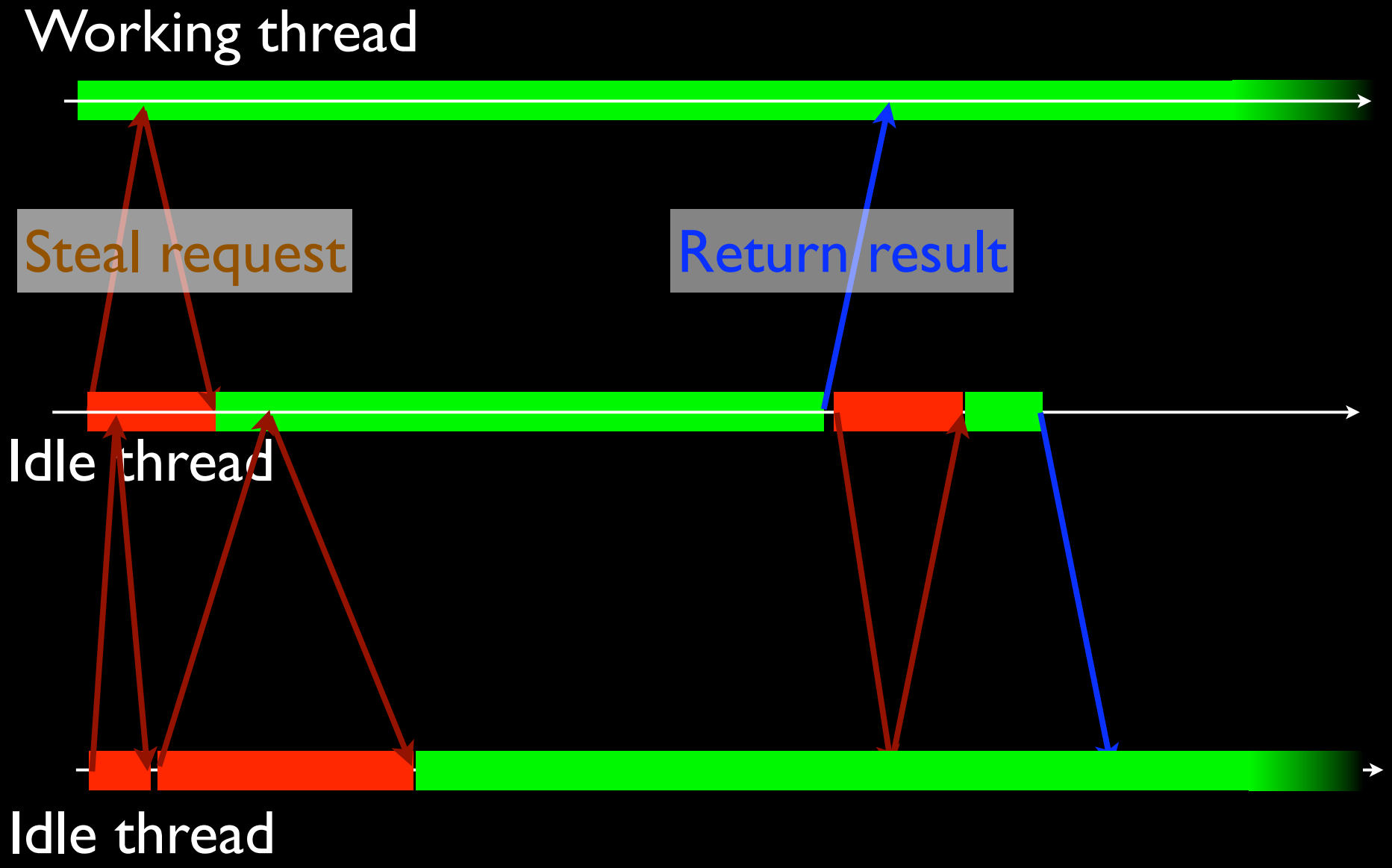

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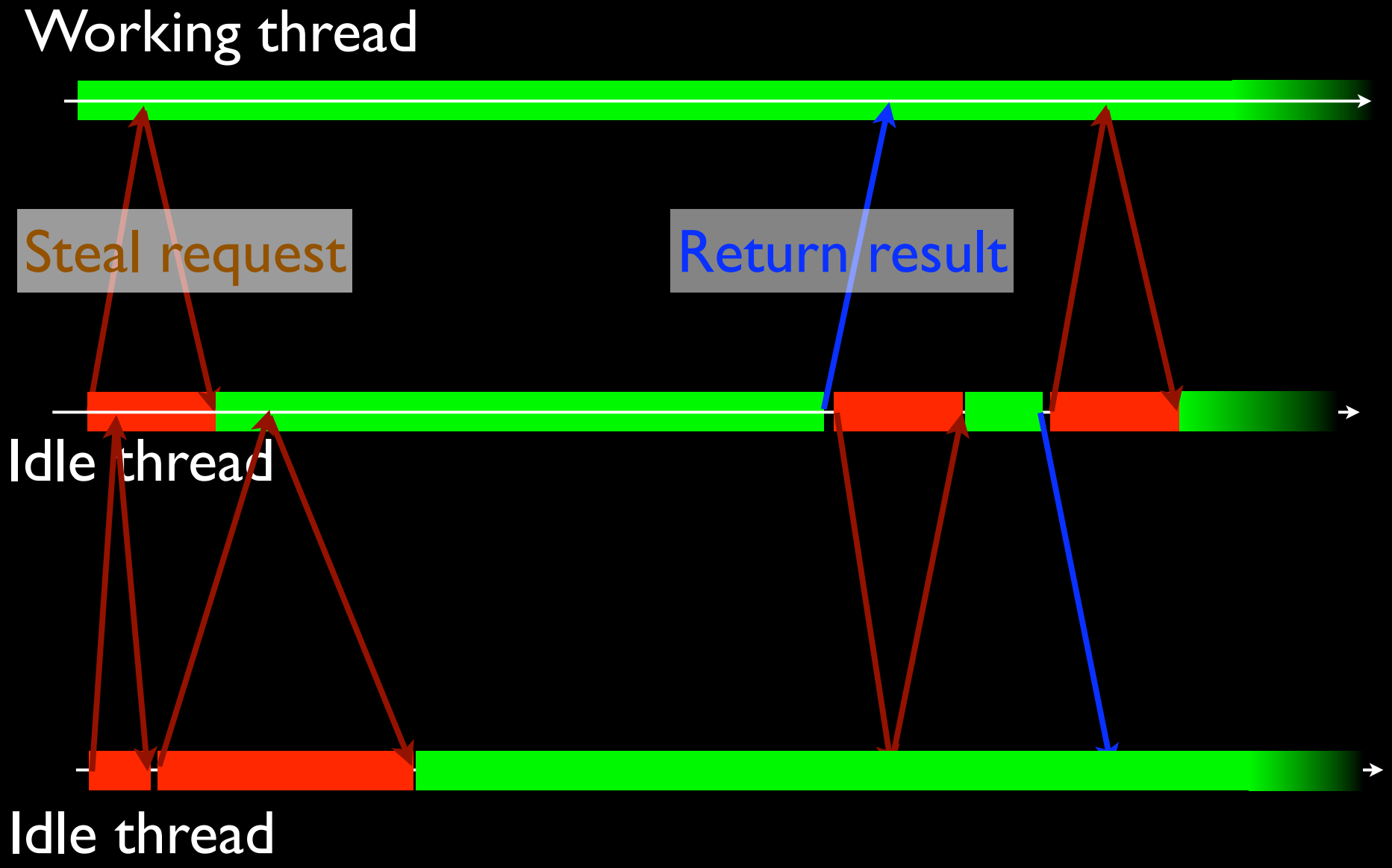

Work stealing queue

- Task: basic unit of computation
- Each thread has its own work queue
  - push(task) -> () : push a task
  - pop() -> task : pop a task
  - push / pop: LIFO order

  } used by the owner thread

- A idle thread can steal task from a victim thread's workqueue
  - steal() -> task : steal a task from the queue
  - push / steal: FIFO order

  } used by the thief thread

- Random selection of victim threads

Assumption/Definitions

- Fork/Join recursive parallel program
  - (formally: strict multithreaded computation)
- Notation:
  - T_{seq} : "sequential work"
  - T_1 : execution time on 1 core of the parallel program, called "work"
  - T_∞ : time of execution on ∞ cores, called the "critical path" or the depth
  - T_p : time of execution on P cores
  - P : the number of processors

Remarks

- $P_\infty \stackrel{def}{=} T_1 / T_\infty$
  - available parallelism (maximum speedup)
  - e.g. Fibonacci(30) = 83040
    - $T1 = 5.285*10^{-2}s$, $T_\infty = 3.08*10^{-7}s$
    - $P_\infty \approx 171591$

- T_1 / T_{seq}
  - measure the work overhead
    - the creation of tasks
    - the work queue management (push/pop)

Theoretical bound

- Using work stealing scheduler with random selection of victim, the expected time on P processors is:

$$T_p = O(T_{seq} / P + T_\infty)$$

- The expected number of steal requests per thread X_p is:

$$X_p = O(T_\infty)$$

- [Blumofe, Leiseron, Focs 94, PPoPP 95], [Arora, Blumofe, Plaxton, SPAA 98], ...

With data flow graph ?

- Previous bounds: “fork/join” program
  - all created tasks are ready
- Not true in data flow program
  - complexity to compute data flow constraints

- Fortunately, the same bound holds
  - [Galilée, Doreille, Cavalheiro, Roch, PACT 98]
  - [Gautier, Roch, Wagner, ICCS2007]
    - in general case, the sequential execution is a valid execution
      - do not compute data flow constraints except on rare events

Remarks

- Other interesting results
  - Space efficient
  - "Same" bounds for heterogenous machines (dynamic speeds) with slightly modified work stealing
    - [Bender, Rabin, SPAA00]

$$T_p = O(T_{seq} / (P \prod_{avrg}) + \beta T_\infty / \prod_{avrg})$$

- If $P << P_\infty$

➡ quasi linear speed up : $T_p \sim c_1 T_{seq} / P$

- Interest of fine grain parallel algorithm ($T_\infty << T_1$)

➡ $P_\infty >> 1$!! allows wide range of quasi linear speedup

Practical bound

- Cilk 95
  - c_1 ~ from 1 to 25, depends on the application
  - $c_\infty \sim 1$
  - $T_p \approx c_1 T_{seq}/p + c_\infty T_\infty$
- Athapascan/Kaapi
  - 1998: $T_1/T_{seq} \sim 1 - 10000$: bad representation !
  - 2004: $T_1/T_{seq} \sim 1 - 1000$: optimization
  - 2006: $T_1/T_{seq} \sim 1 - 100$: stack representation
  - 2008: $T_1/T_{seq} \sim 1 - 20$: + data flow constraints computed during steal operation

Related work

- Cilk [94, 95, 98]
  - one of the first language: 3 keywords cilk_spawn, cilk_sync, cilk_for
  - sequential semantic !!!!
  - theoretical guaranteed performance
  - shared memory
- Tascell [09]
  - indolent closure creation (on demand)
  - distributed
  - using same idea as a Cilk extension [96] that has never been tested
- X10 [04, 08]
  - experimental language for HPC
  - extend class of parallel program with work stealing strategy
- Satin [01], Capsule [06]

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- Athapascan/Kaapi [99, 03, 05, 07]
  - macro data flow: 2 keywords Fork, Shared
  - sequential semantic !!!!
  - theoretical guaranteed performance
  - shared & distributed memory
  - fault tolerant protocols
  - fine grain parallelism
    - adaptive algorithm [TSI05 Fr, Europar06, Europar08]
    - cooperative work stealing [09 Fr]

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How to reduce T_{seq}/T_1?

- Why ? => WORK overhead
  - extra instructions from the sequential program
  - especially for short computation (->STL algorithms)
- Three technics
  1. adapt the grain size: stop parallelism after a threshold
     - but: increase T_∞, reduce the average parallelism and increase the number of steal requests
     - difficulty to adjust it automatically
  2. reduce the cost to create task
     - ...ideally do not create task !
  3. optimize the cost of workqueue operations
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$$T_\infty=2\log_2 n,\ T_1=2n$$

  - Fish's lower bound: any parallel algorithm with critical path $\log_2 n$ requires at least $4n$ operations

Adaptive algorithm

- [Roch, Traoré 07], [Roch, Traoré, Gautier 08]
  - Principe: create tasks when processors are idle !
- Task = apply $F(a_i)$ for all elements a_i of an array

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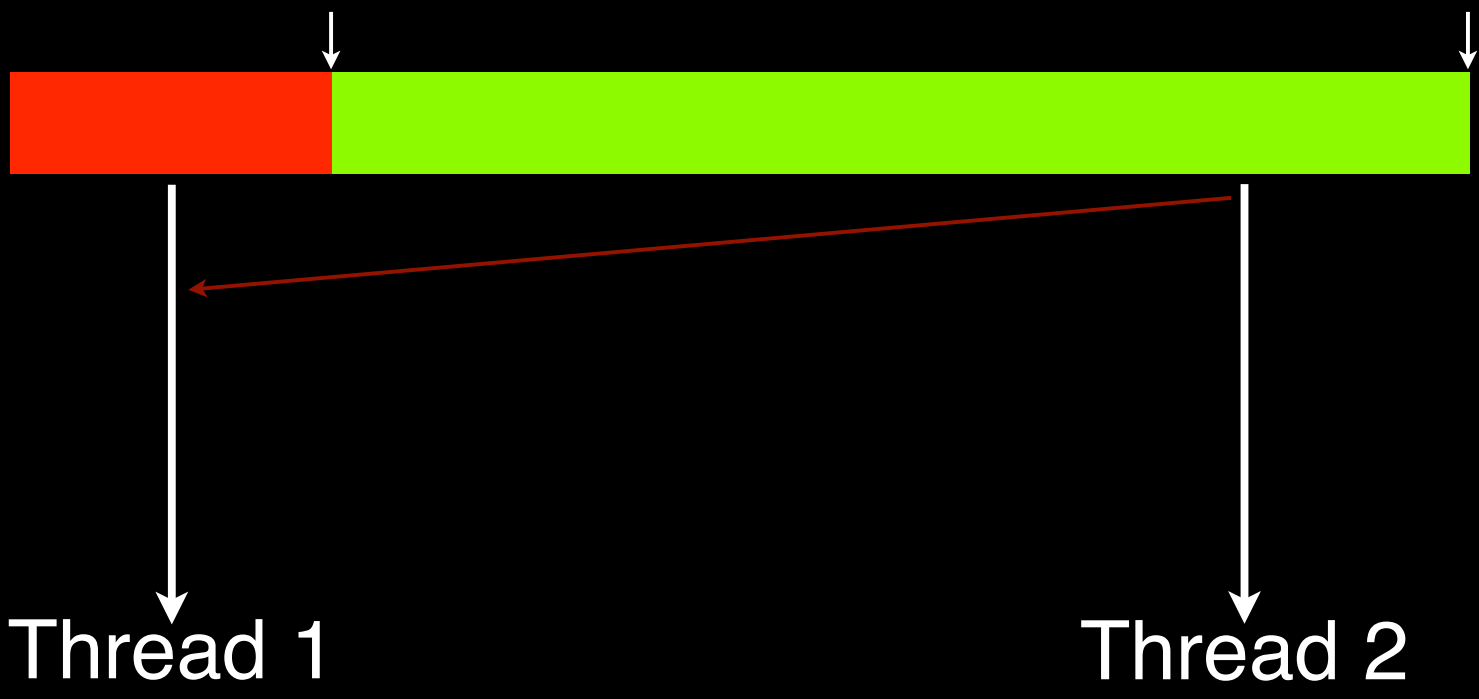

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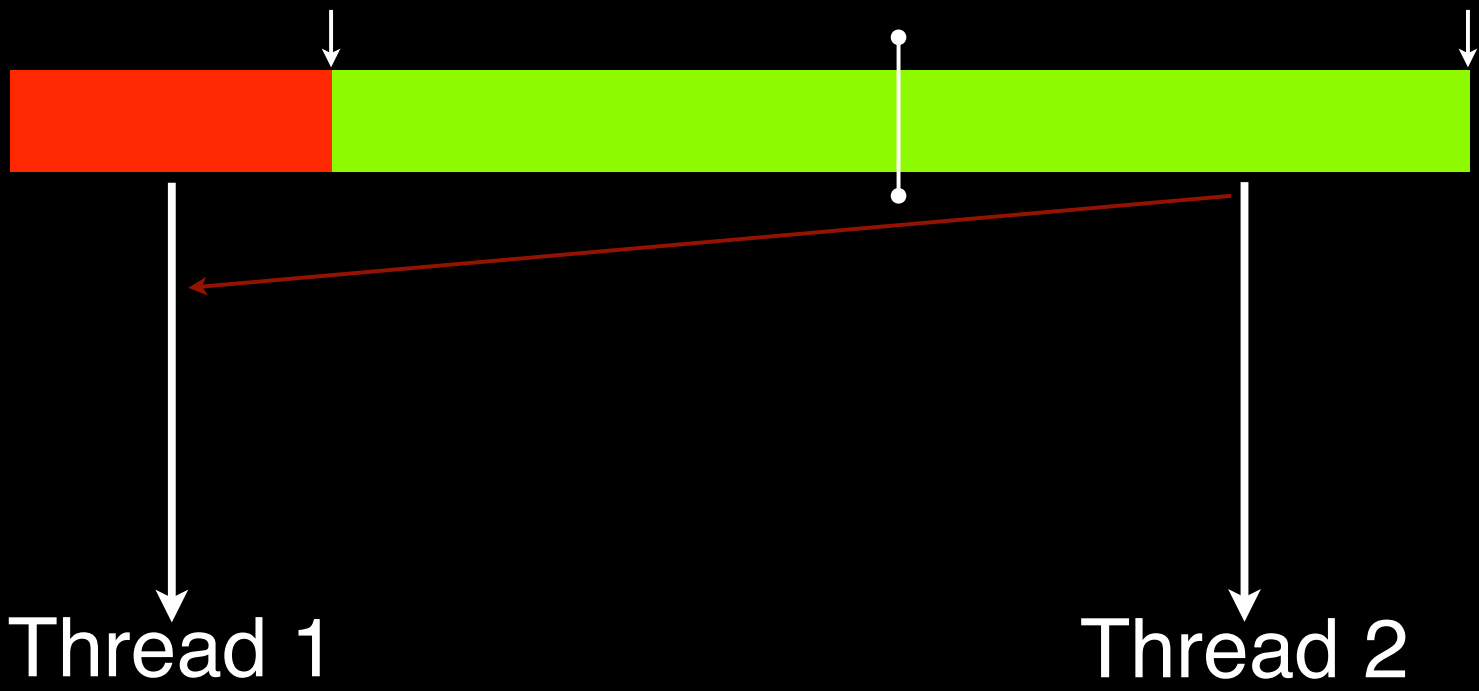

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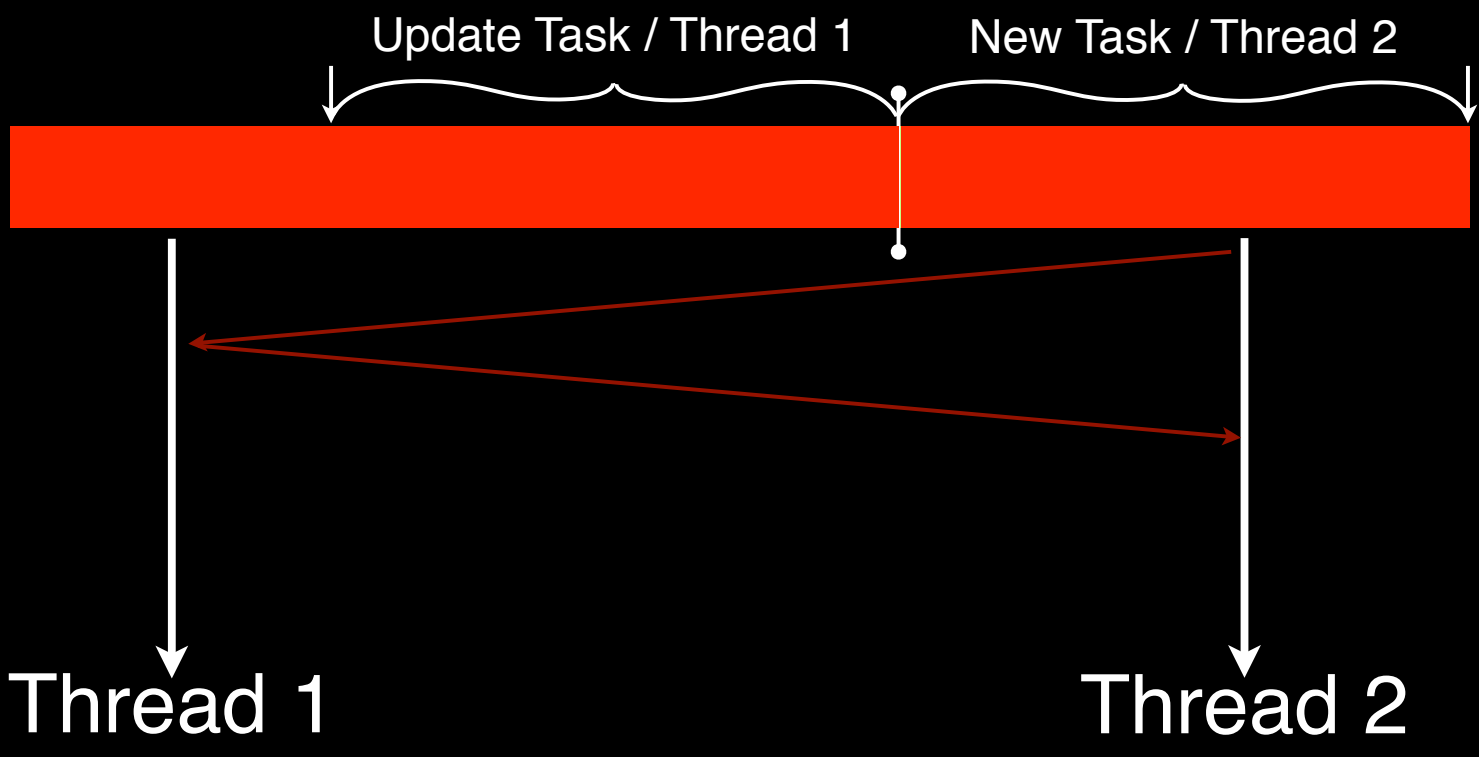

Adaptive algorithm

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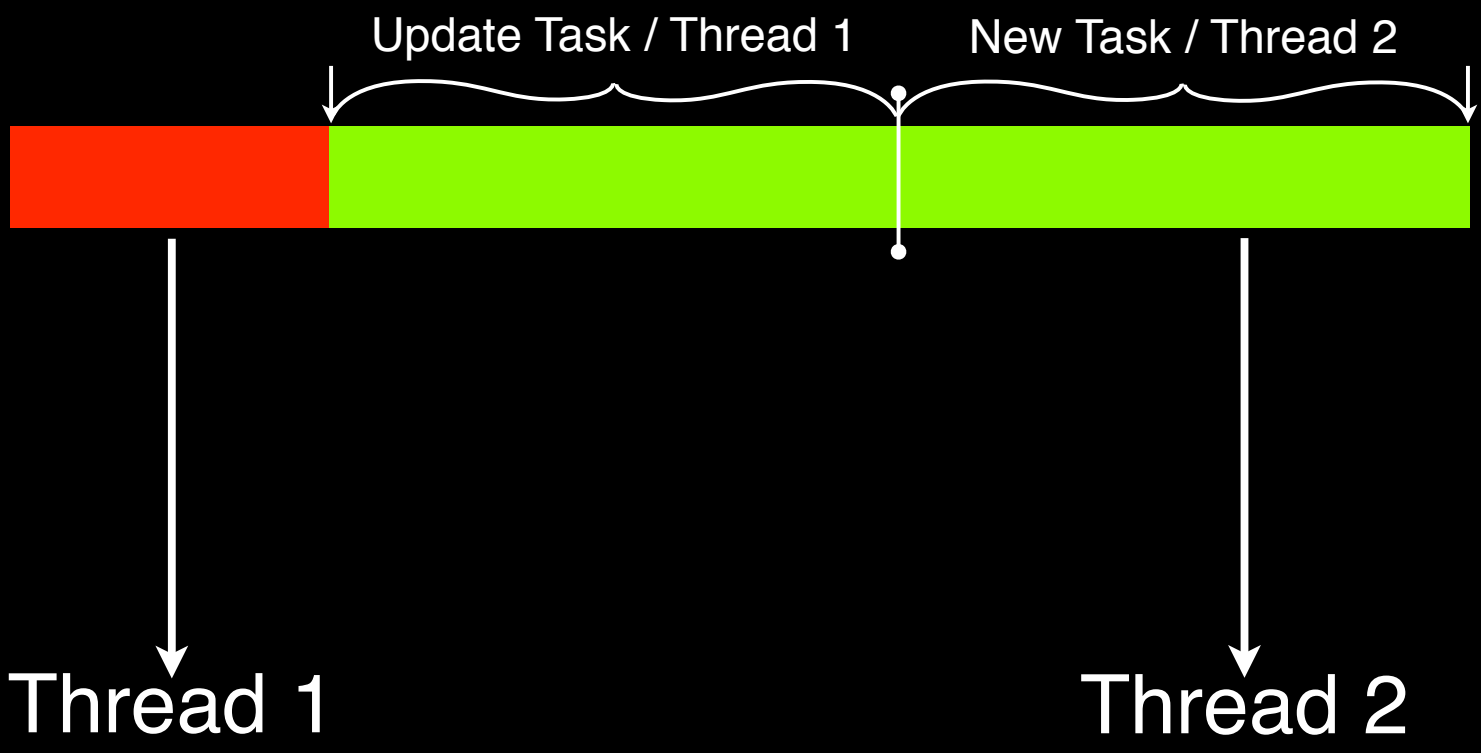
  - Thread 2 is slower or as more work to do



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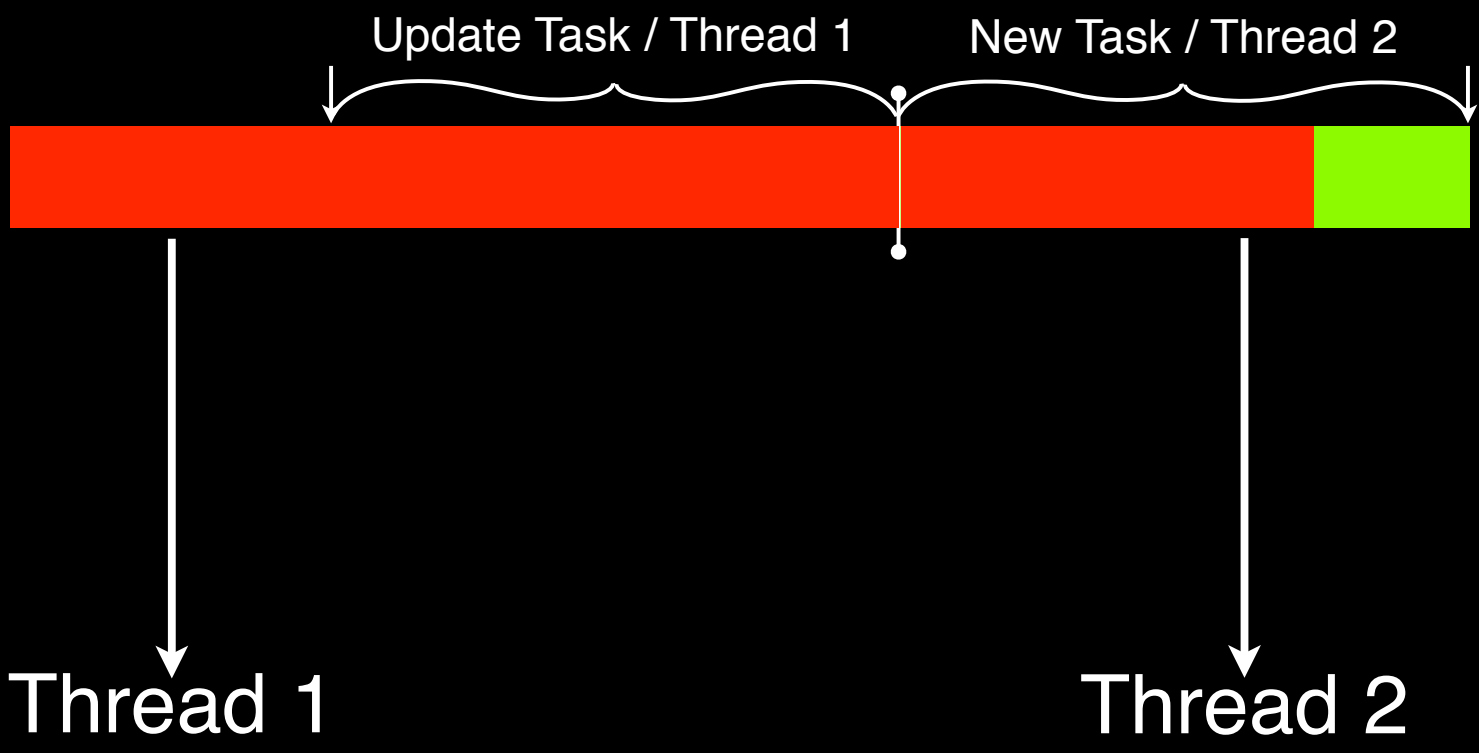
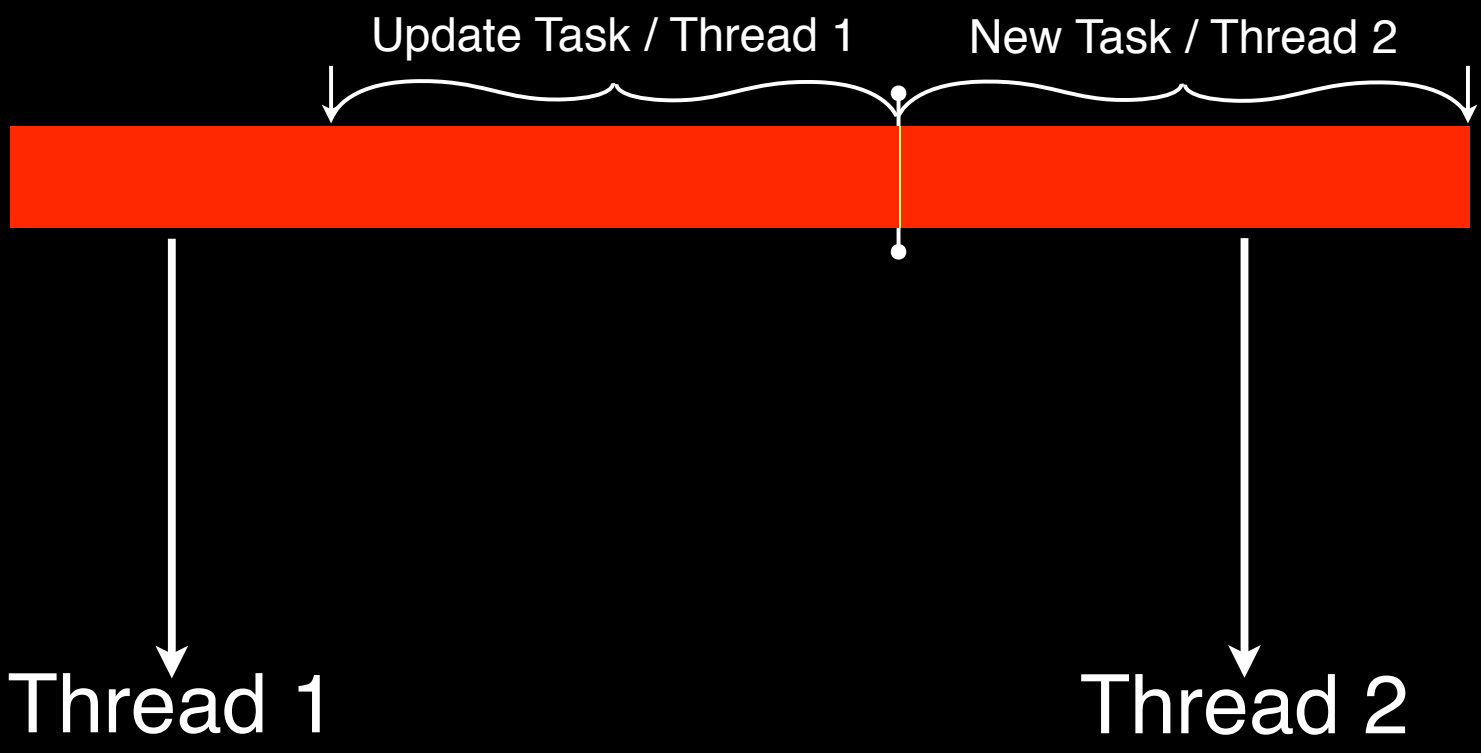


Adaptive algorithm

- Case of heterogeneous speed
  - Thread 2 is slower or as more work to do



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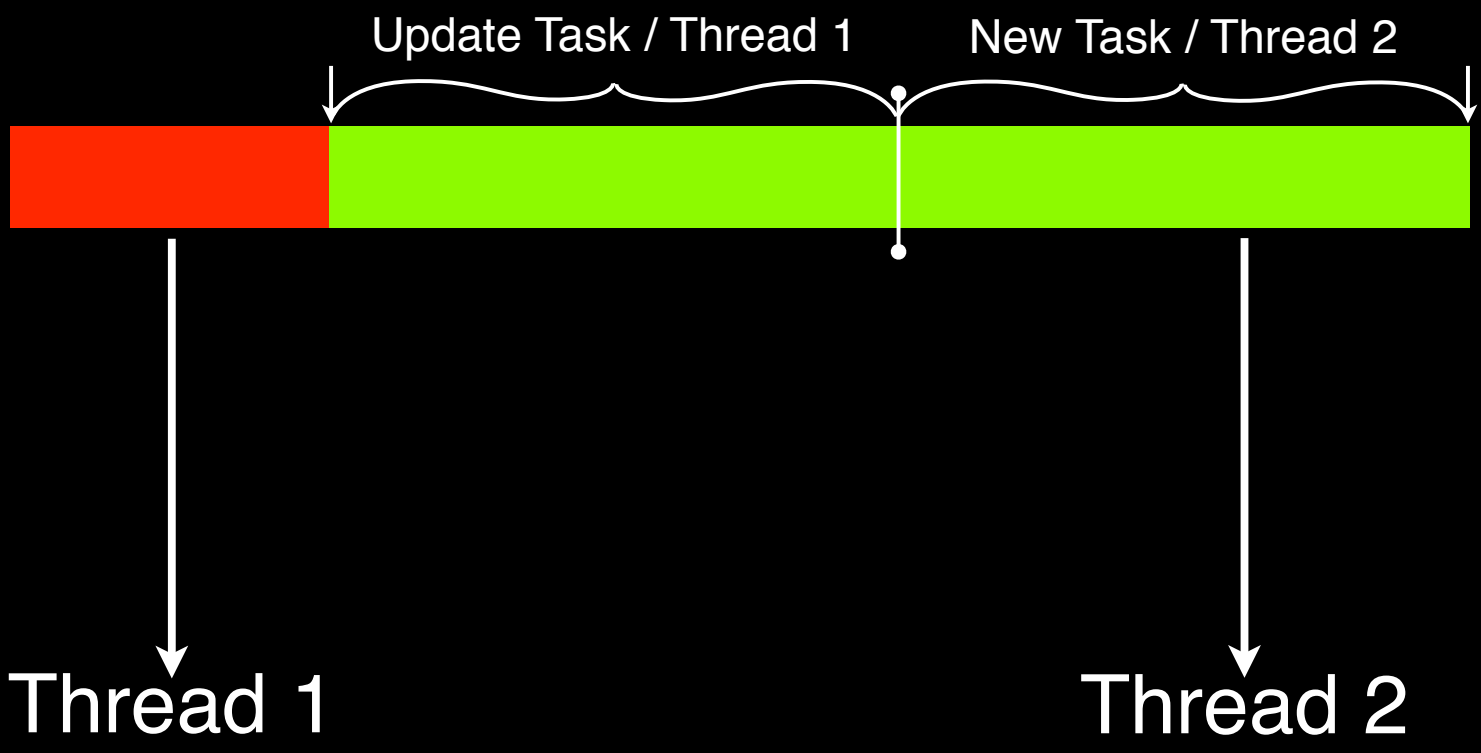

Adaptive algorithm

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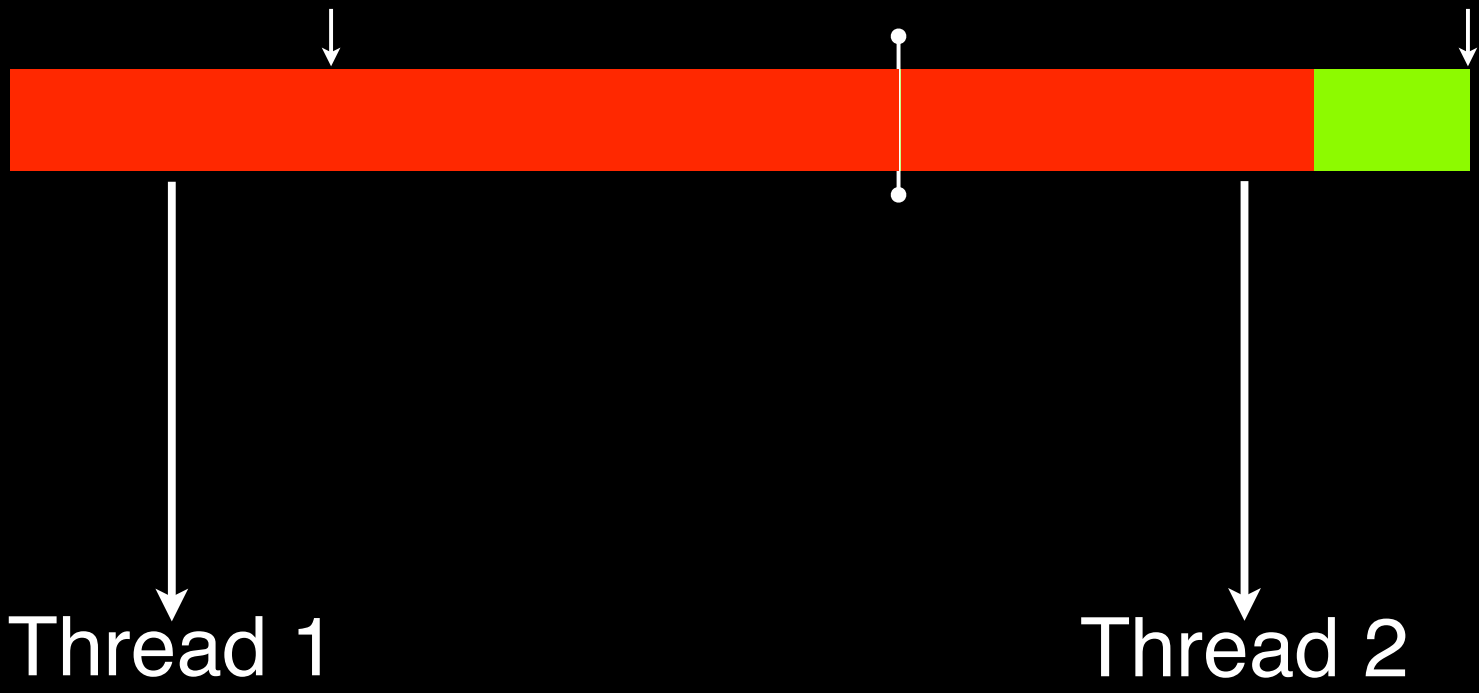

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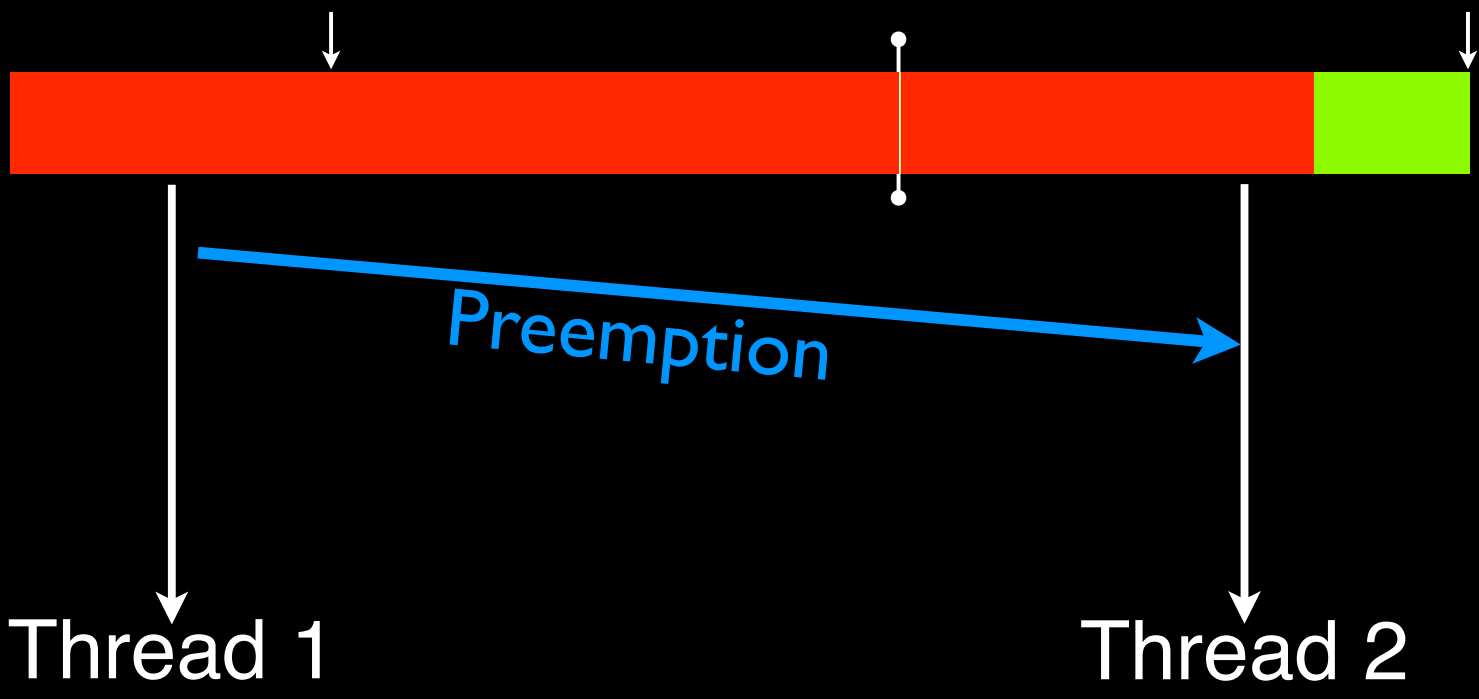

Adaptive algorithm

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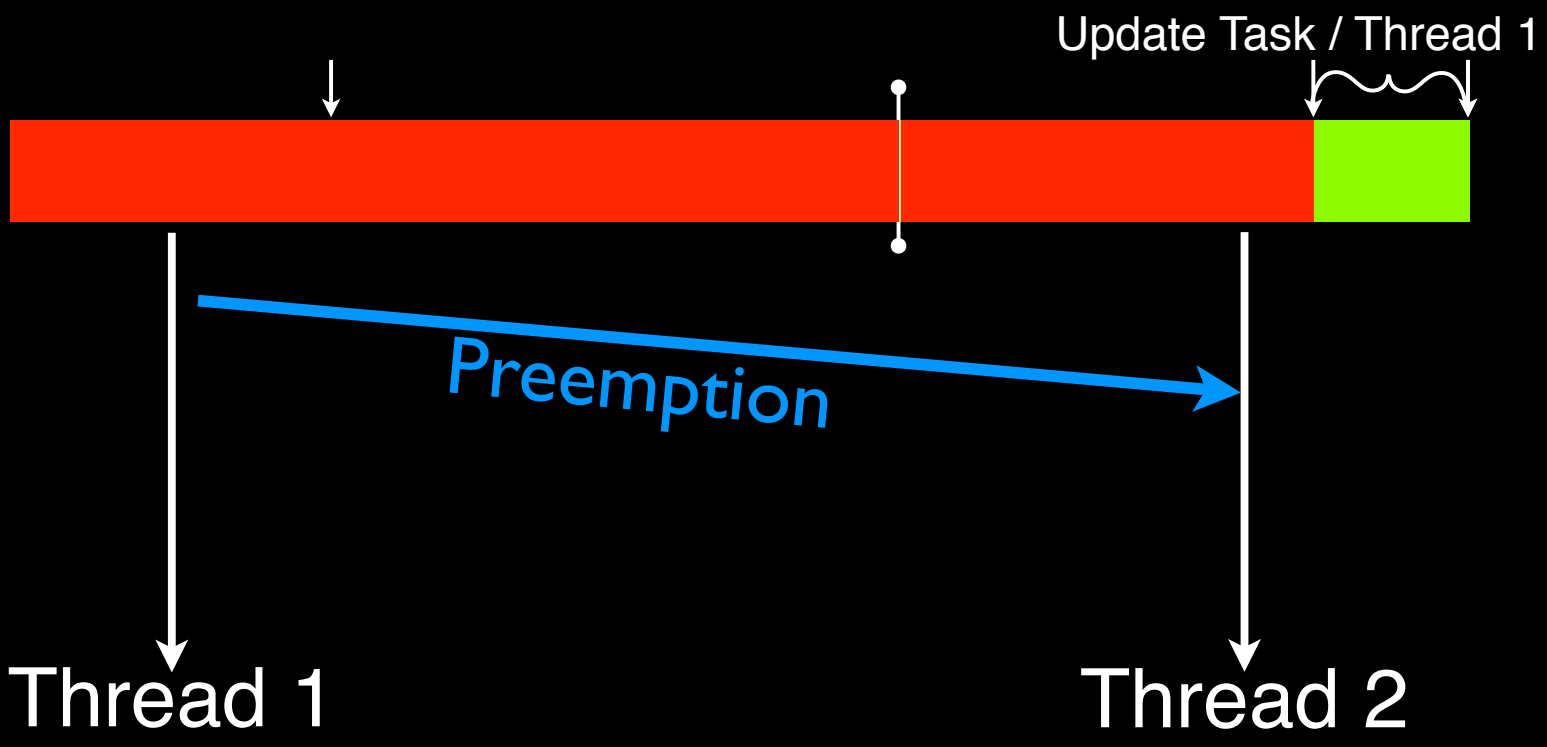
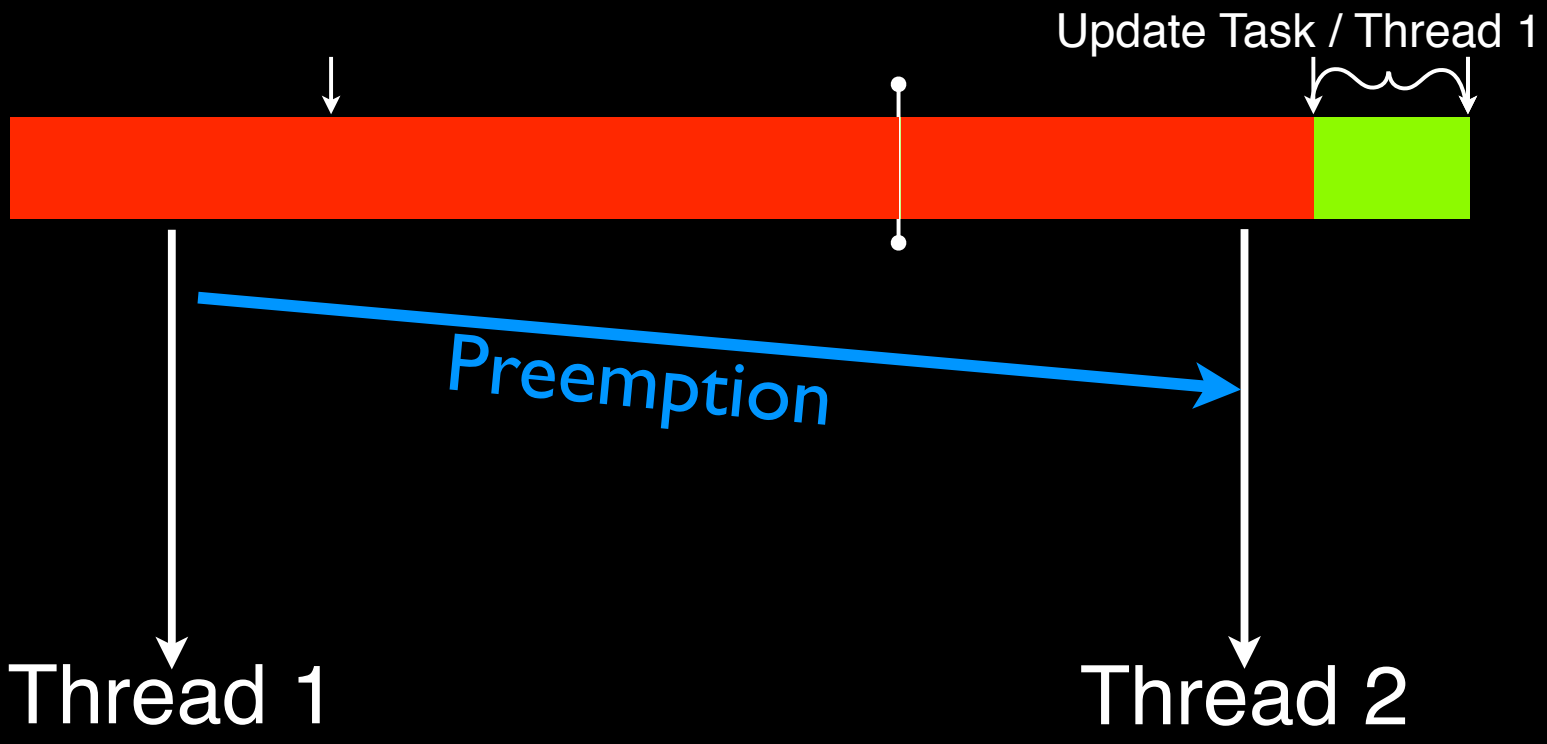


Adaptive algorithm

- Case of heterogeneous speed
  - Thread 2 is slower or as more work to do
  - We always use preemption: main thread (sequential algorithm) preempts thieves



Algorithmic point of view

- 2 Algorithms
  - Sequential: efficiency
  - Parallel: to split work & merge partial results
- Scheduler
  - interleaved execution of the two algorithms depending on the idle CPUs
  - robust to heterogeneous processors

Workqueue optimization

- 3 operations
  - push / pop / steal
- Algorithms
  - Cilk: T.H.E. protocol
    - serialization of thieves to a same victim
    - thief/victim atomic read/write + lock in rare case
  - ABP [SPAA00]:
    - lock free (Compare&Swap), but prone to overflow
  - Chase & Lev [SPAA05]:
    - without limitation (other than hardware)

➡ C O S T L Y 'cas' operation [PPoPP09]

Role of the 'CAS'

- Consensus between N-thieves and the victim
  - In theory, not possible (if wait free) with less powerful synchronization primitive
  - e.g.: atomic register read/write, test&set
- How to avoid 'CAS' ?

Relaxed semantics

- "Idempotent work stealing" [PPoPP09]
  - Maged M. Michael, Martin T. Vechev,
  - Vijay A. Saraswat (work also on X10 language)
  - avoid CAS in pop operation

➡ More Performance

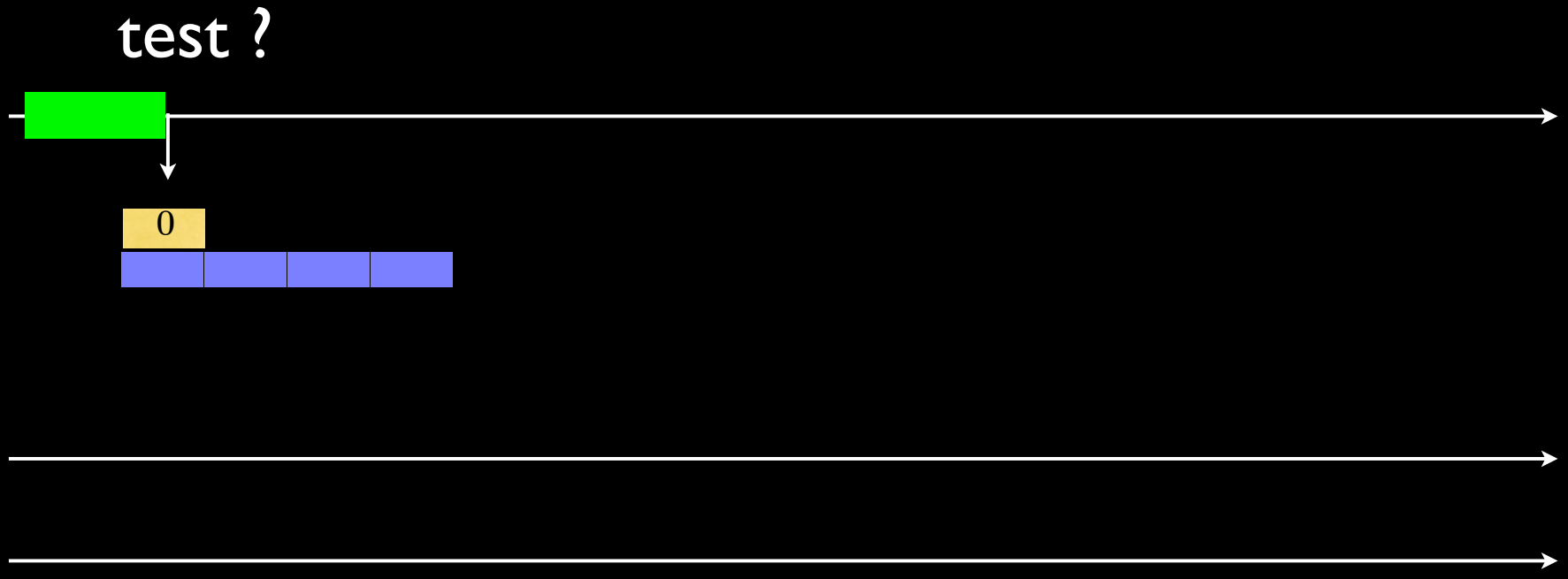
- Drawback
  - a task is returned (and executed) at least once
  - ... instead of exactly once

Cooperative approach

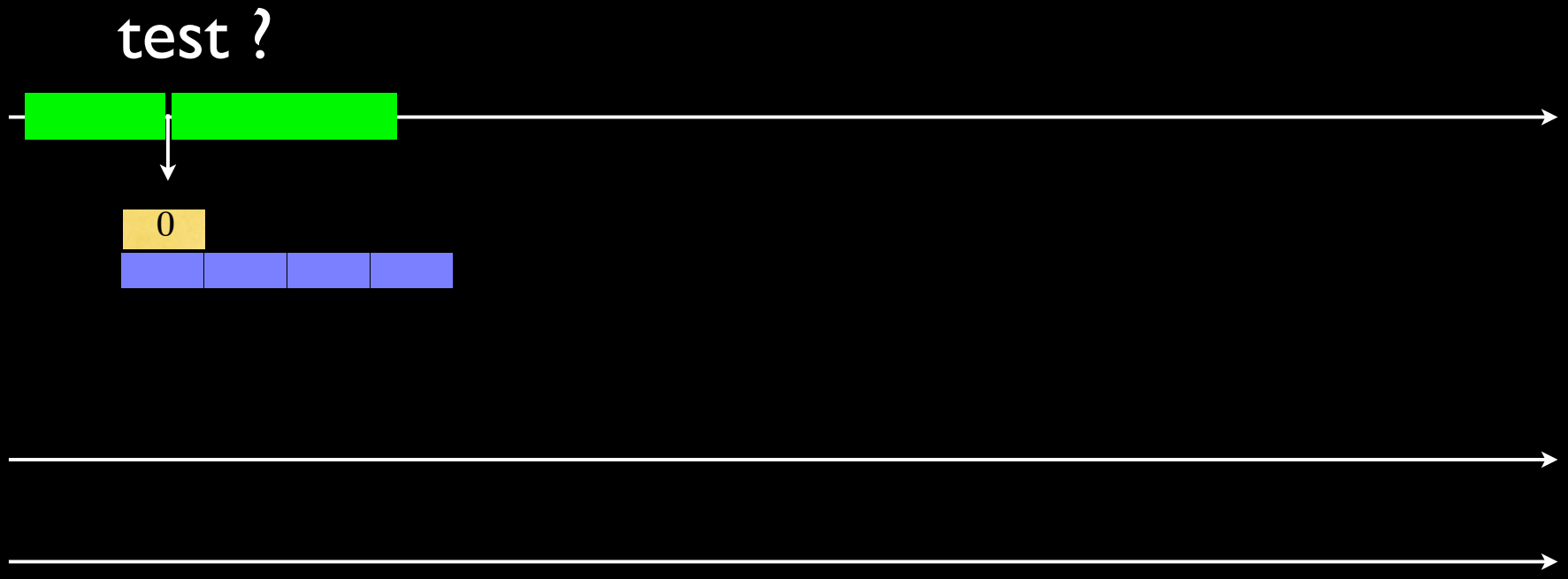
- [X. Besseron, C. Laferrière]
- Keep same semantics as usual
  - a task is extracted exactly once
- so...avoid concurrency between victim & thieves
  - the victim interrupts its work to process steal requests
  - some similarity with TasCell [09], Capsule [06]
- Drawback
  - the victim should poll requests
  - thieves are waiting

Cooperative WS

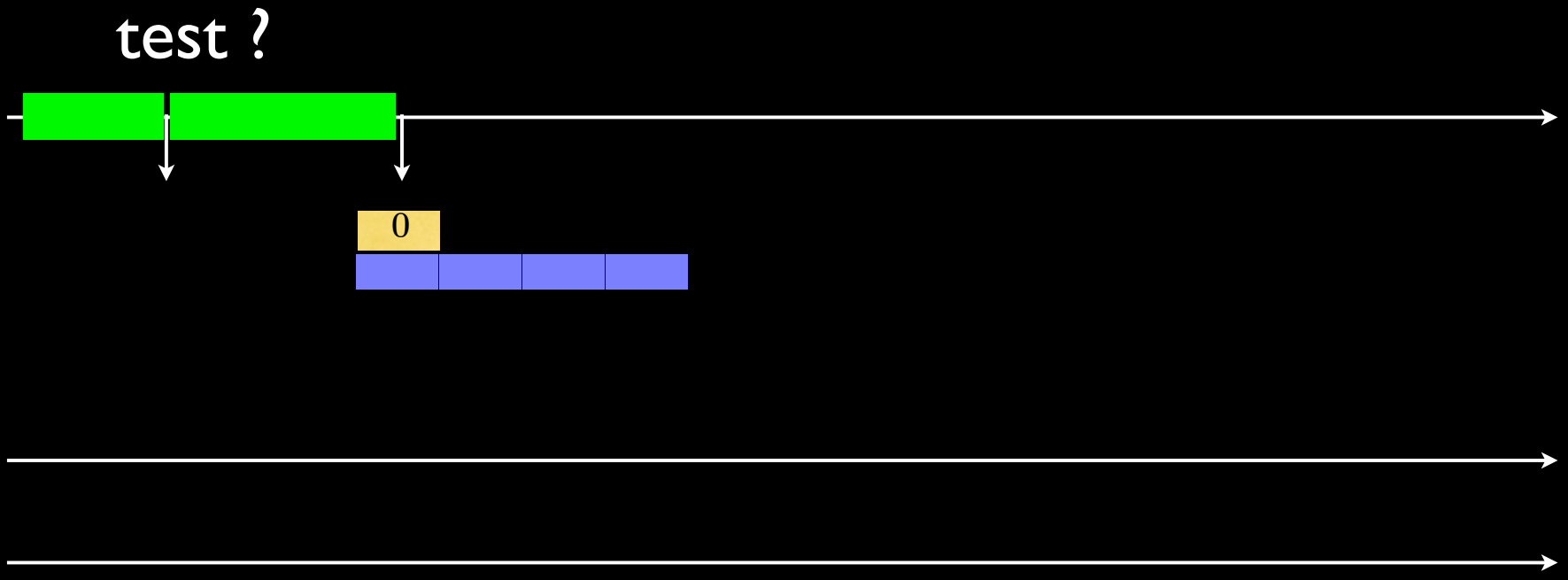
Cooperative WS



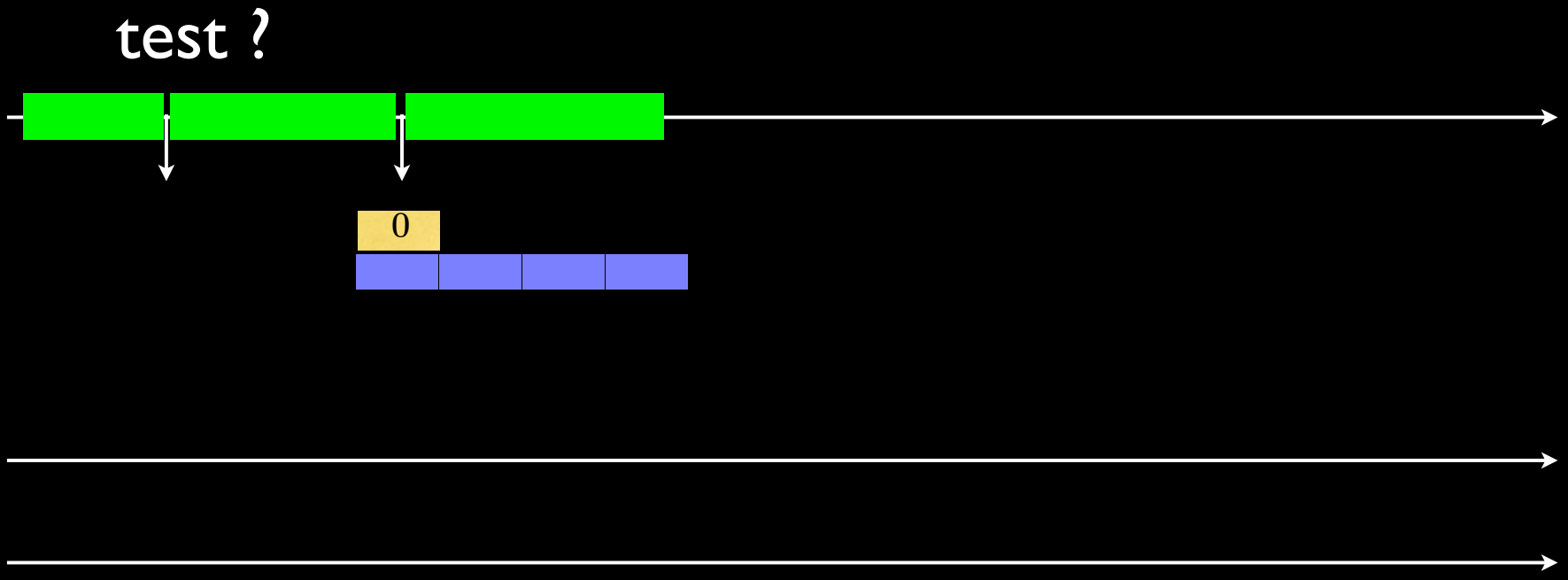
Cooperative WS



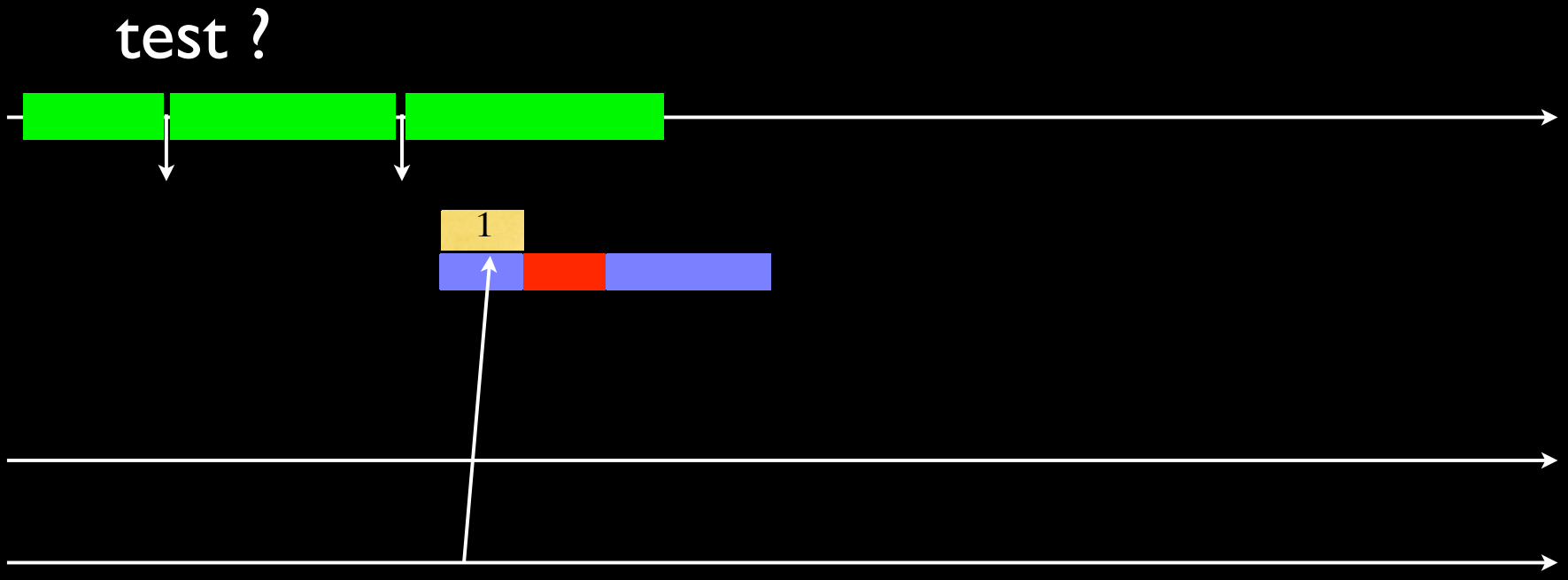
Cooperative WS



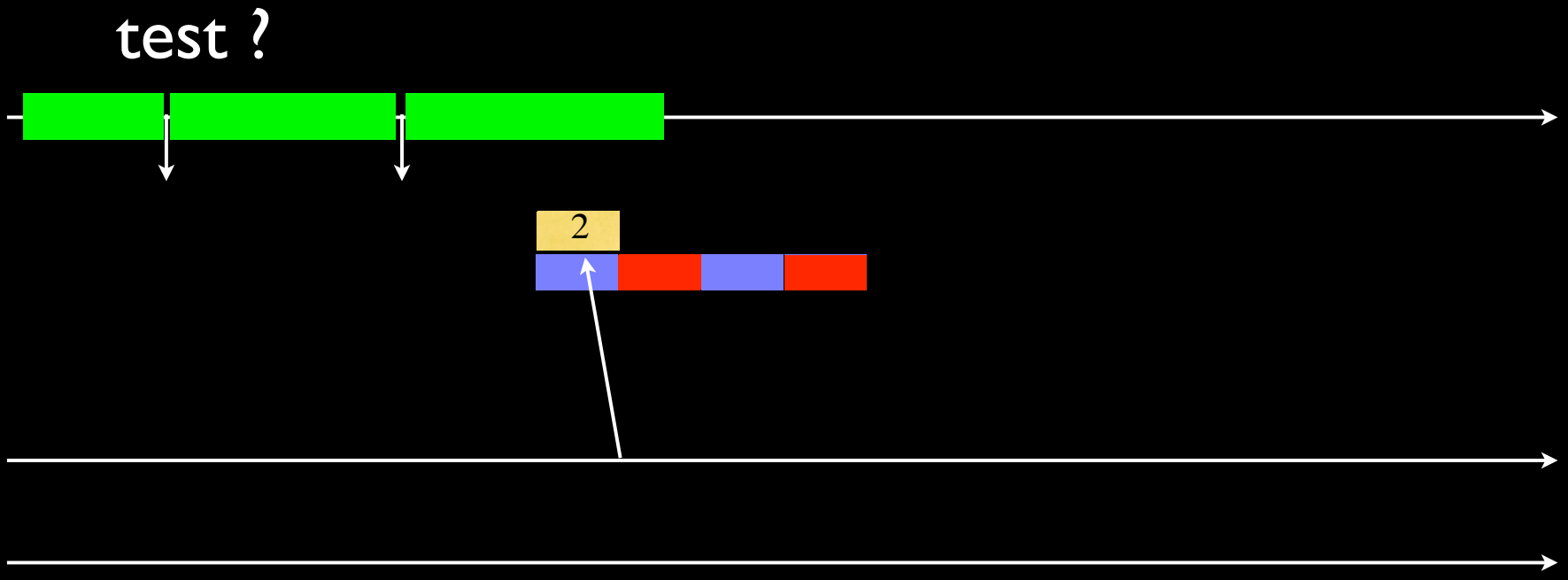
Cooperative WS



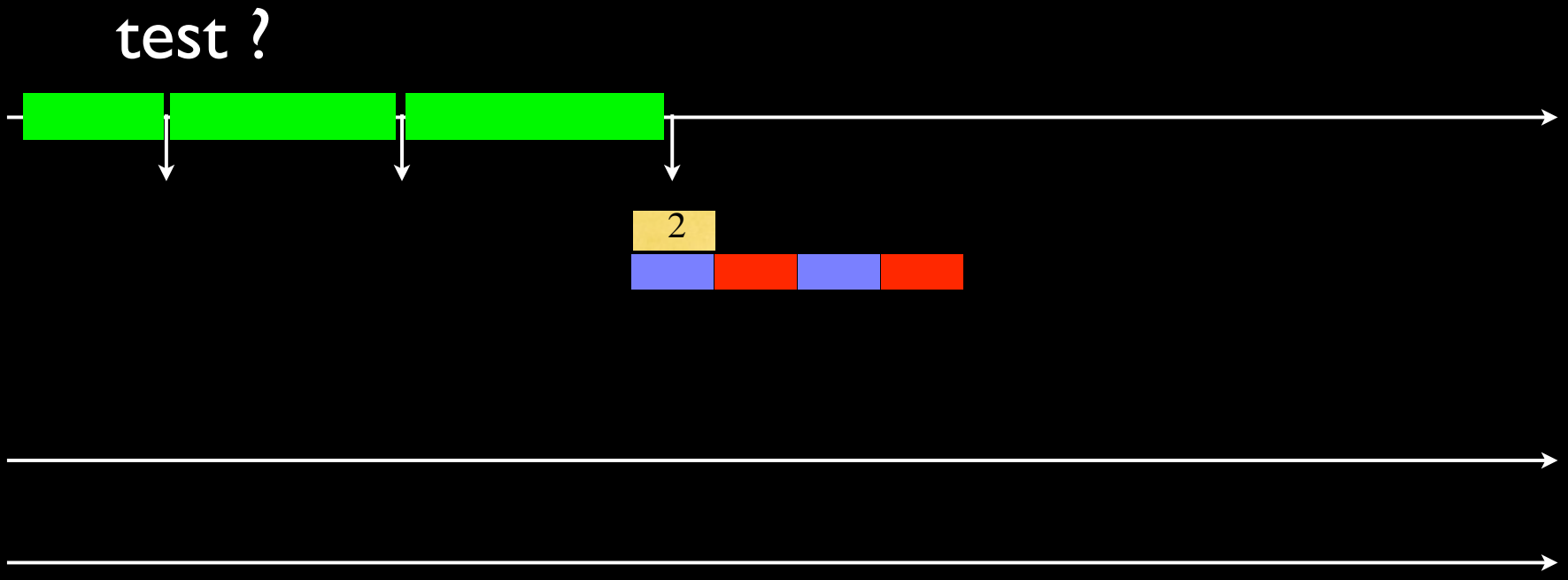
Cooperative WS



Cooperative WS



Cooperative WS



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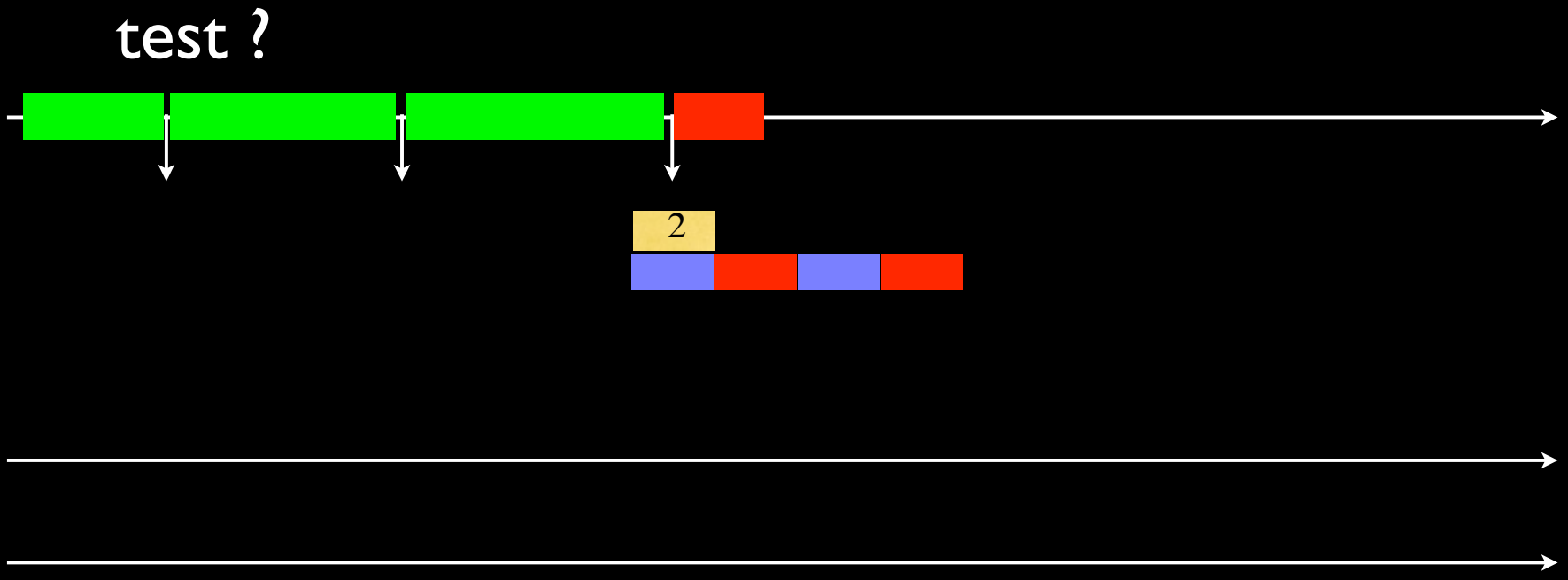

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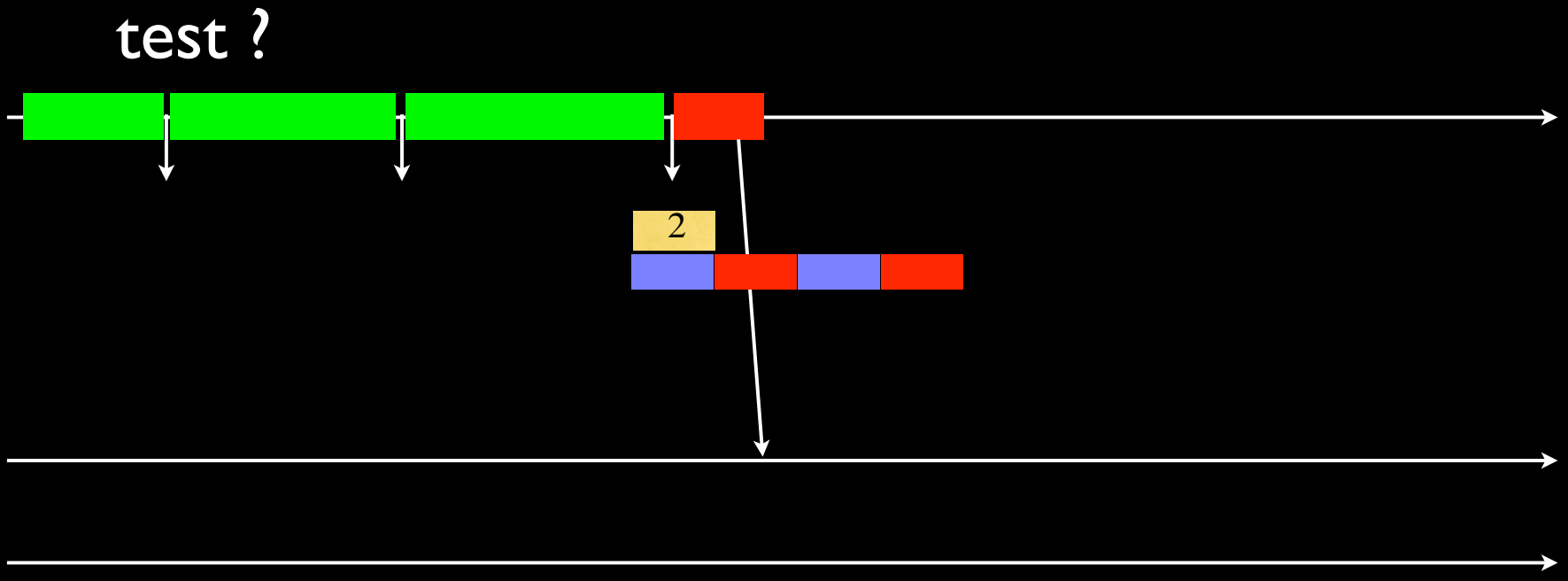
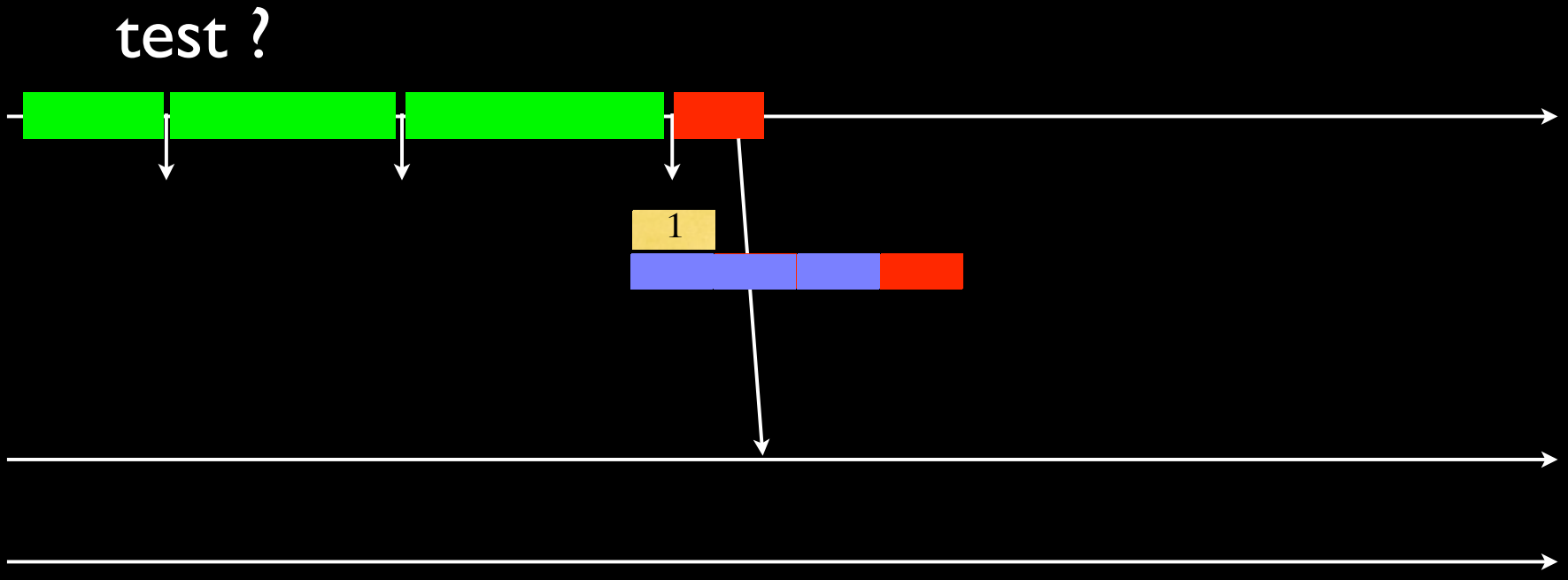
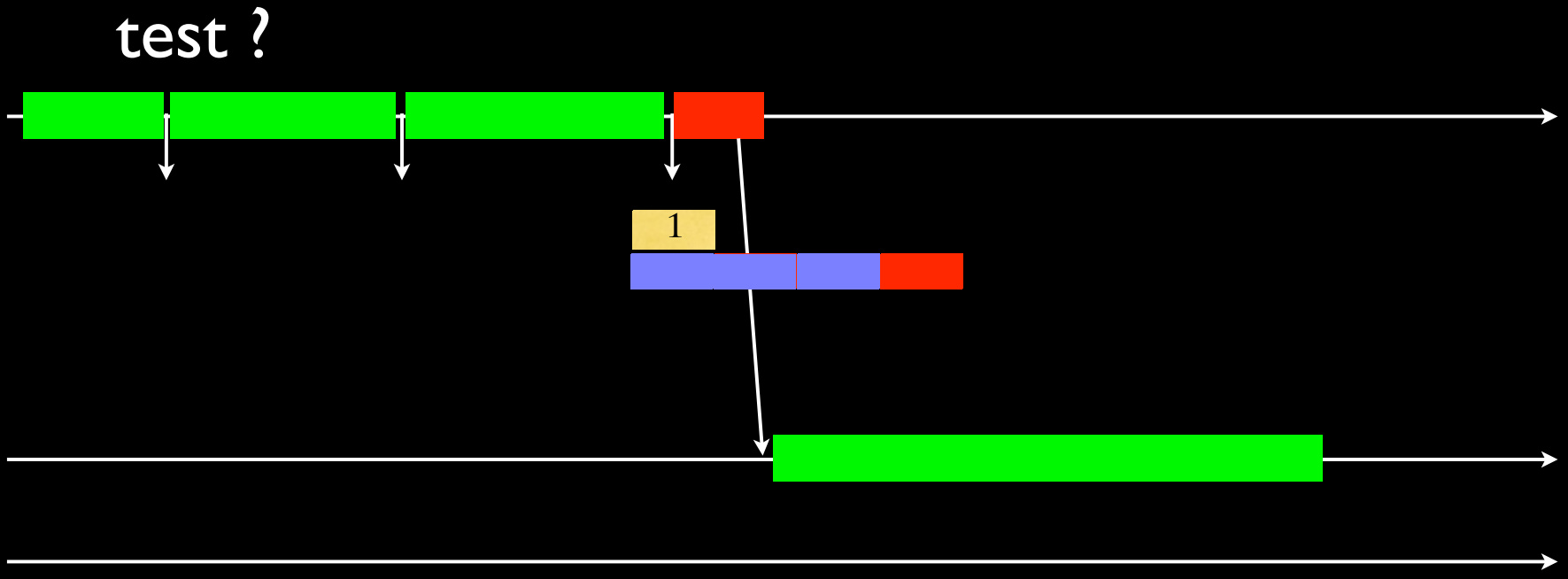


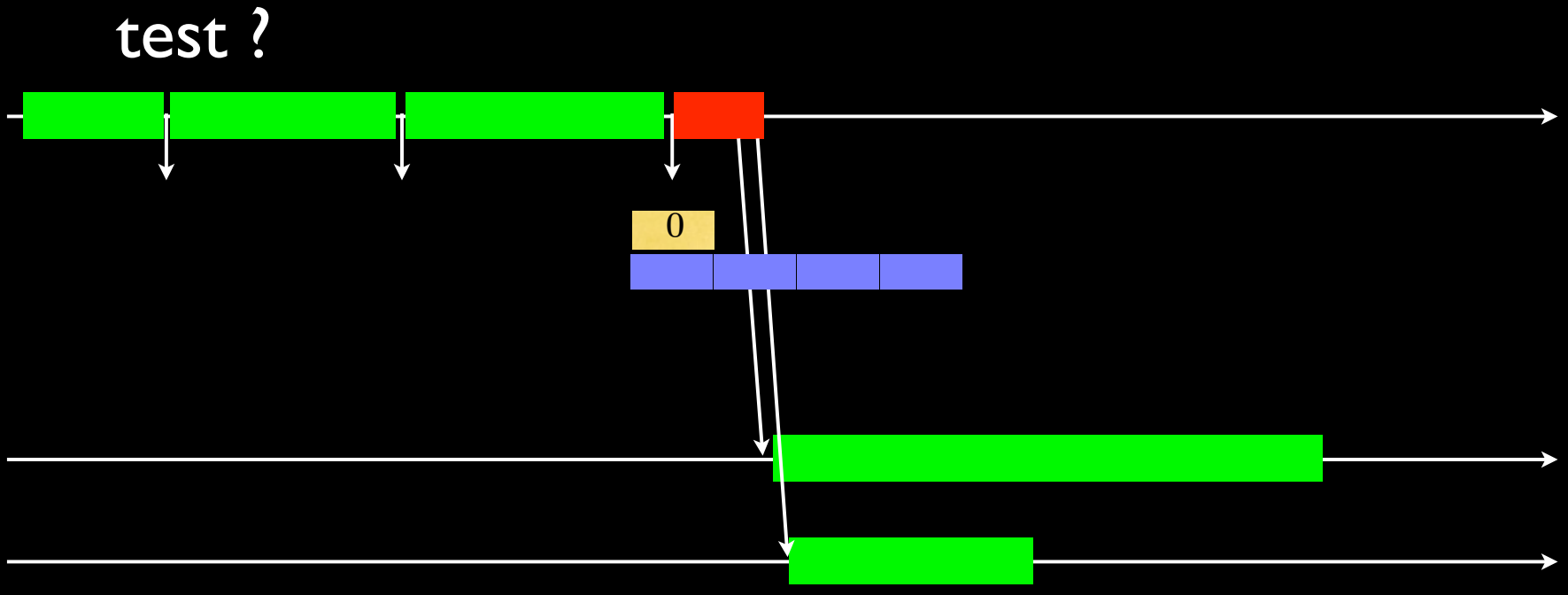
Cooperative WS



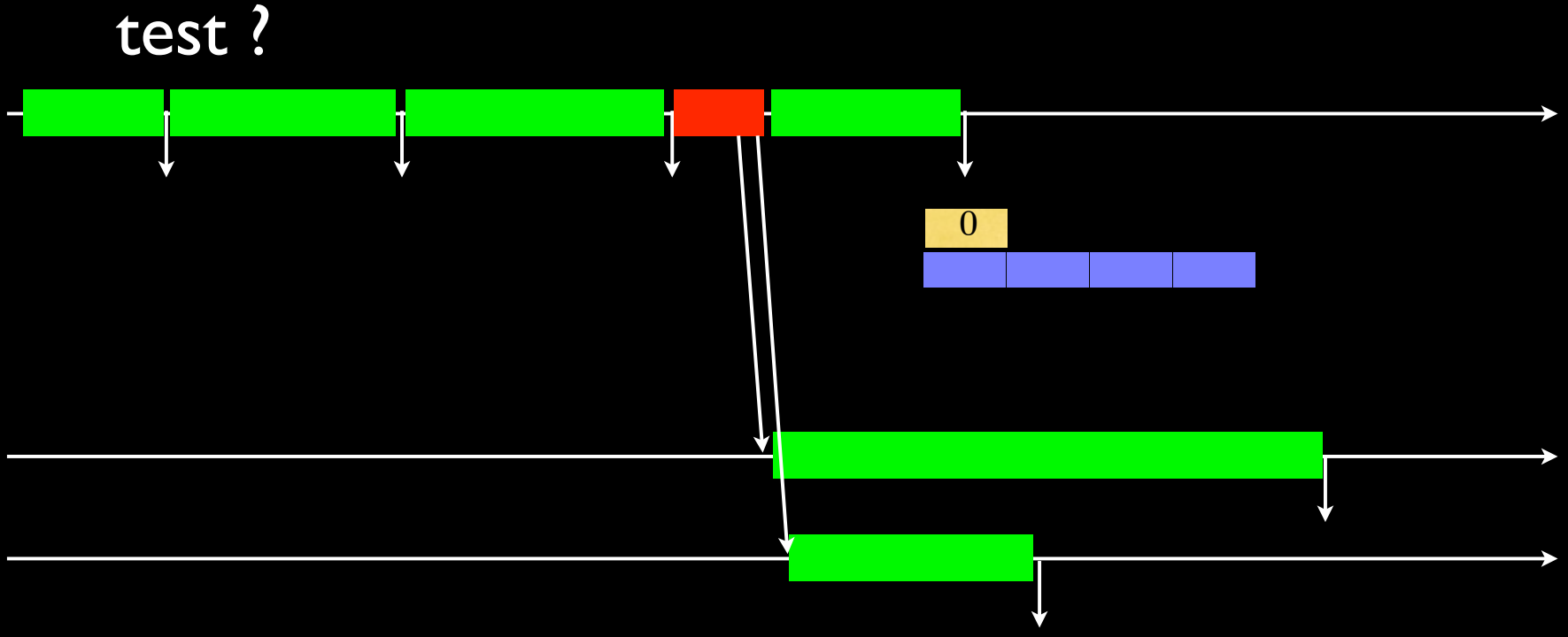
Cooperative WS



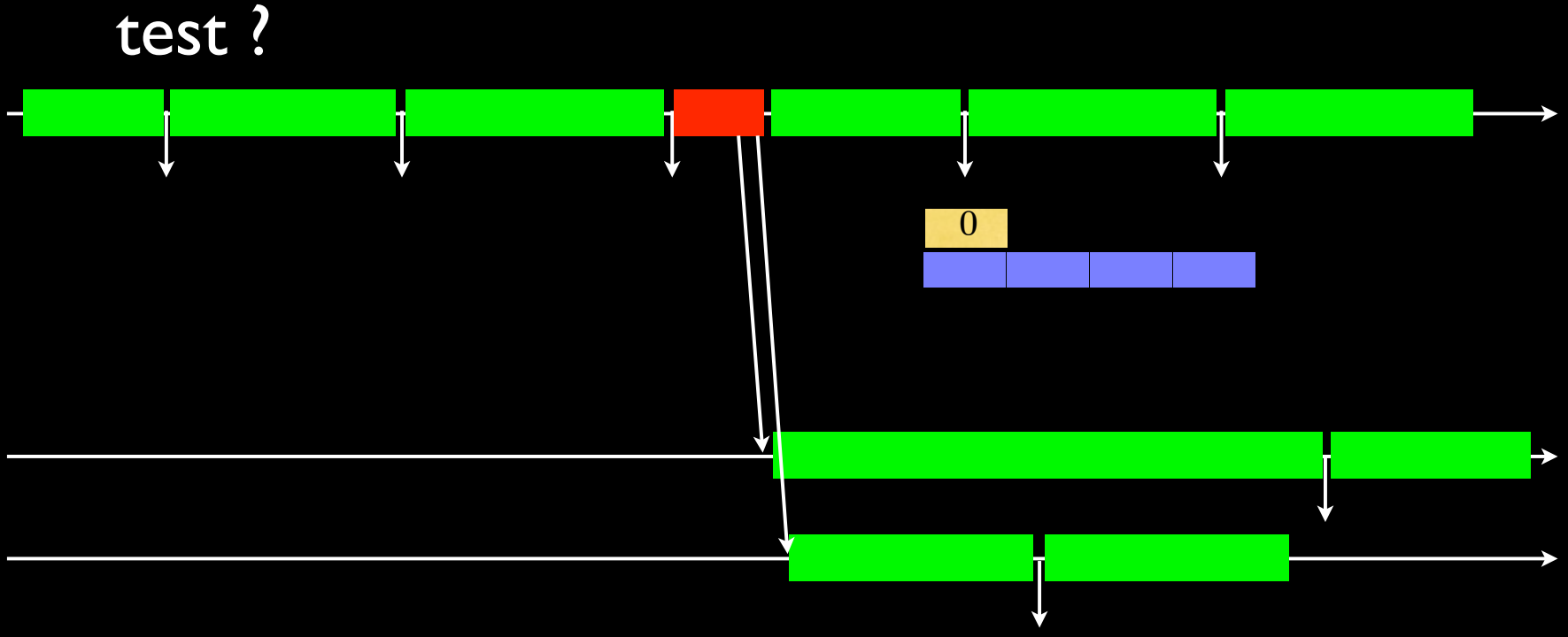
Cooperative WS



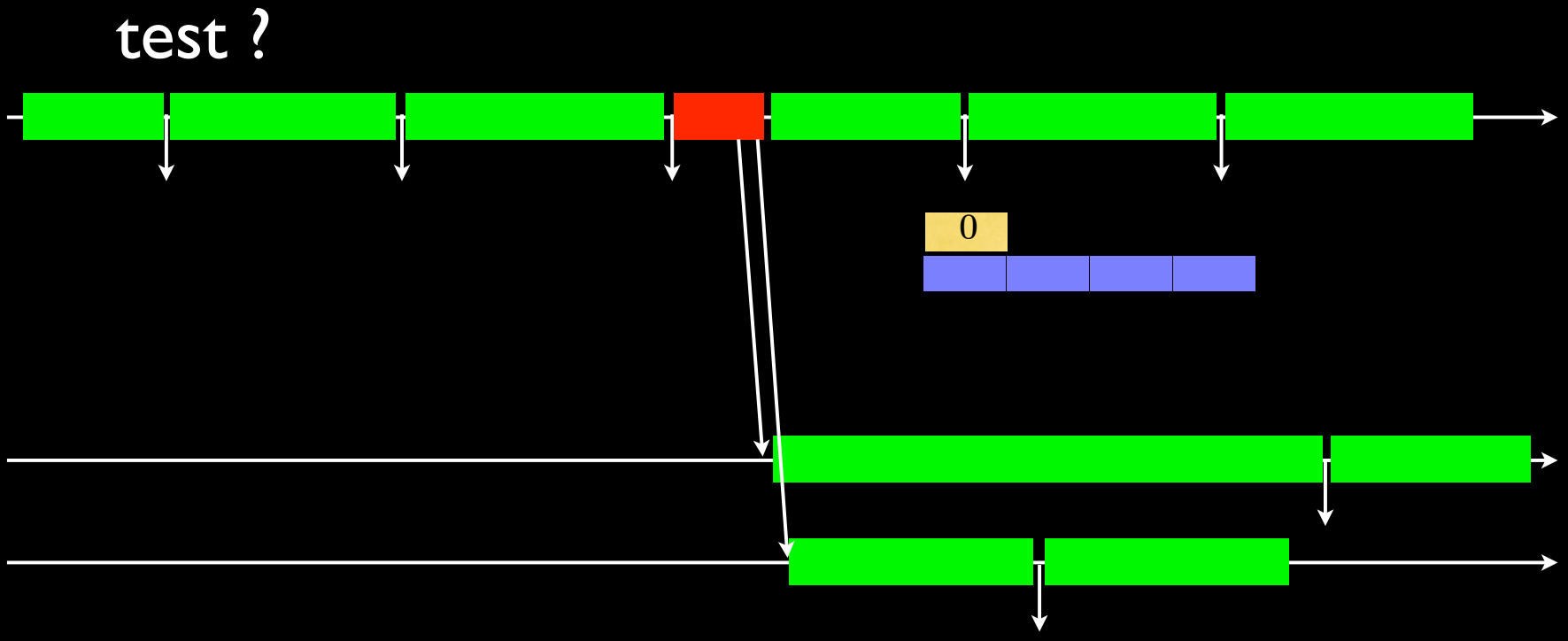
Cooperative WS



Cooperative WS



Cooperative WS



- Gain
  - work overhead: 1 read on memory
  - reply to K thieves in place of only 1
    - better workload balance

Outline

- Athapascan / Kaapi a software stack
- Foundation of work stealing
- Controls of the overheads
- Experiments with STL algorithms

KaSTL: Parallel STL

- [PhD Daouda Traoré, 2008]
- Technics applied to 95% of STL algorithms
  - STL: Standard C++ Template Library
- Comparison with other library
  - Cilk++, Intel Thread Building Block (TBB)
  - MCSTL (GNU STL parallelized with OpenMP)
- Multiprocessor : 8 AMD CPUs with 2 cores

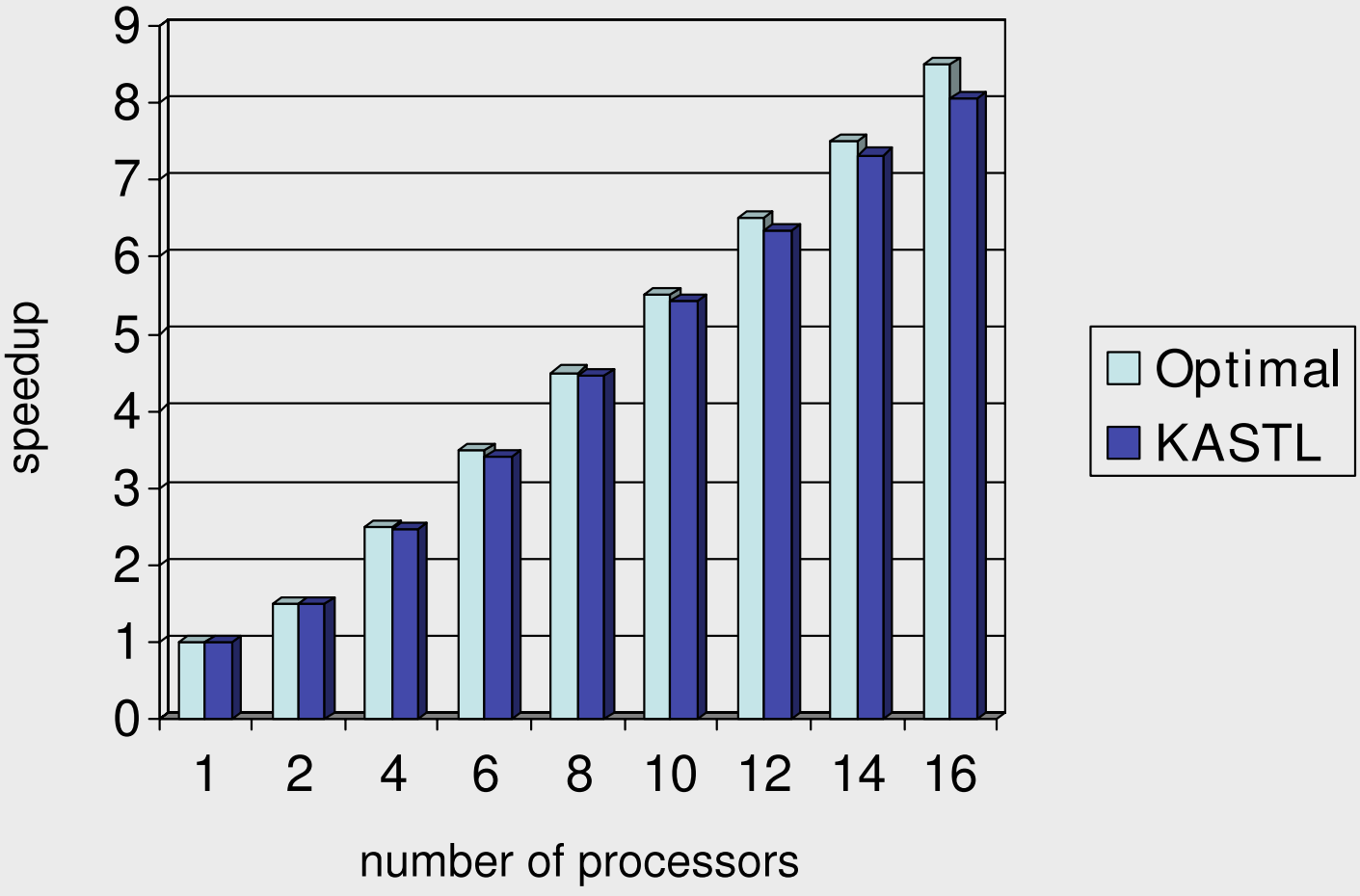
Experiments

- Two set of experiments
  - 1/ with adaptive algorithms
    - PhD of [Daouda Traoré]
  - 2/ with cooperative work stealing
    - [Daouda Traoré, Xavier Besseron, Christophe Laferrière]

- Methodology
  - average over 30 runs
  - 1 run = average of 100 basic experiments, do not take into account the first experiment

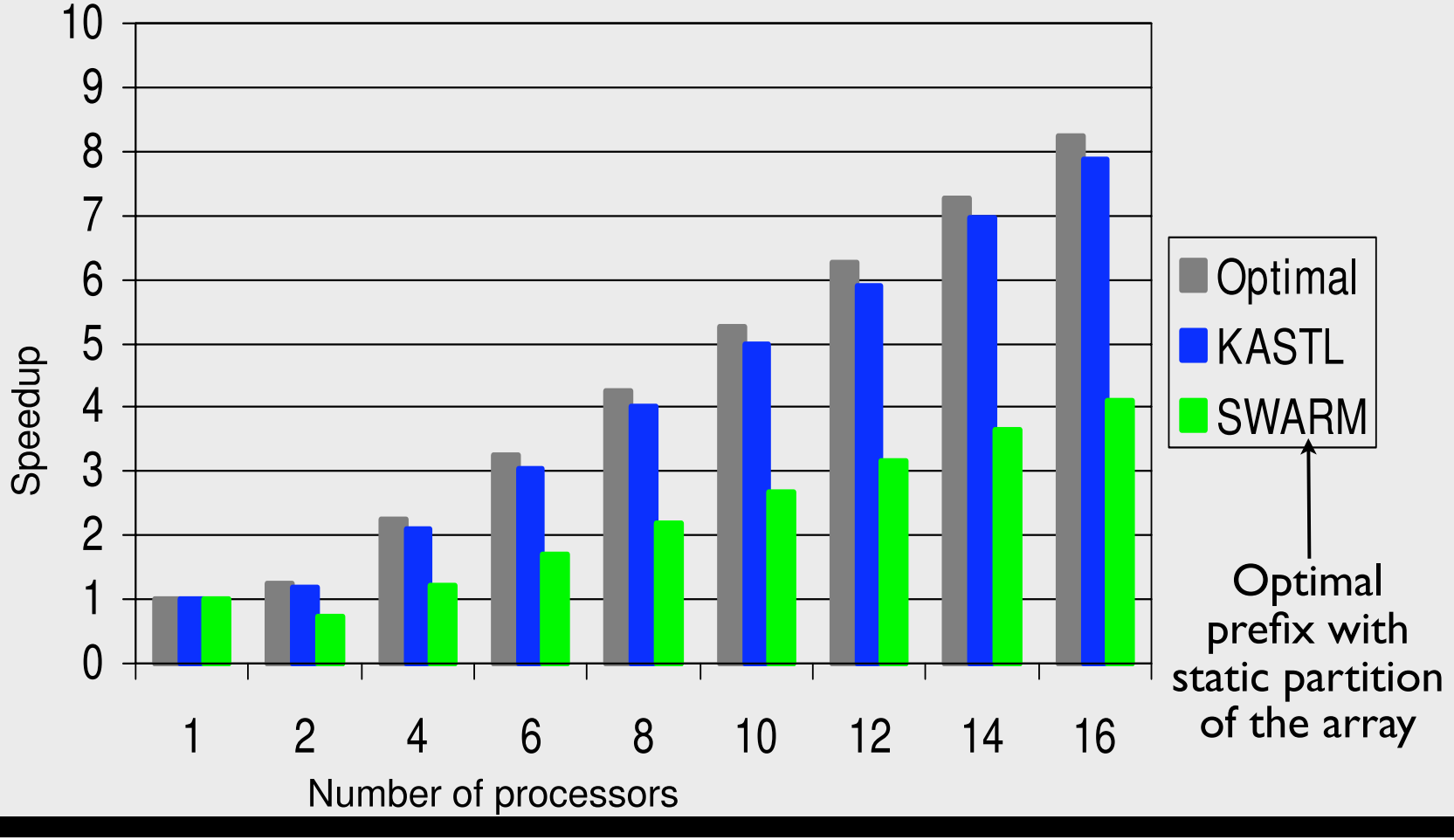
Prefix

- Homogeneous processors
  - * coarse grain, 30000 elements



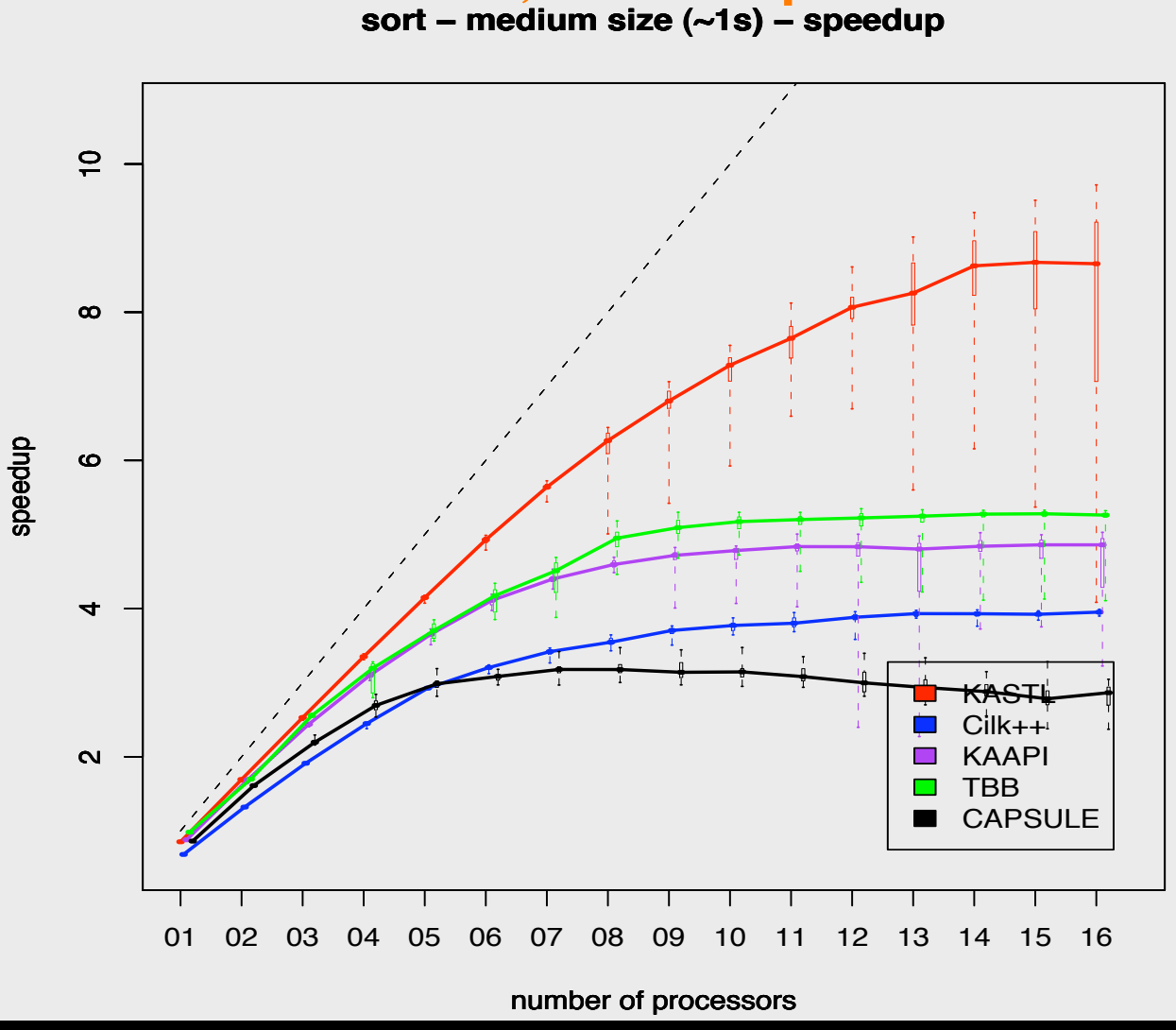
Prefix

- Heterogenous
  - (p−1) processors have the same speed S
  - 1 processor has speed S/2



Sort

- ~ 100M elements, 1s sequential time



Partial conclusion

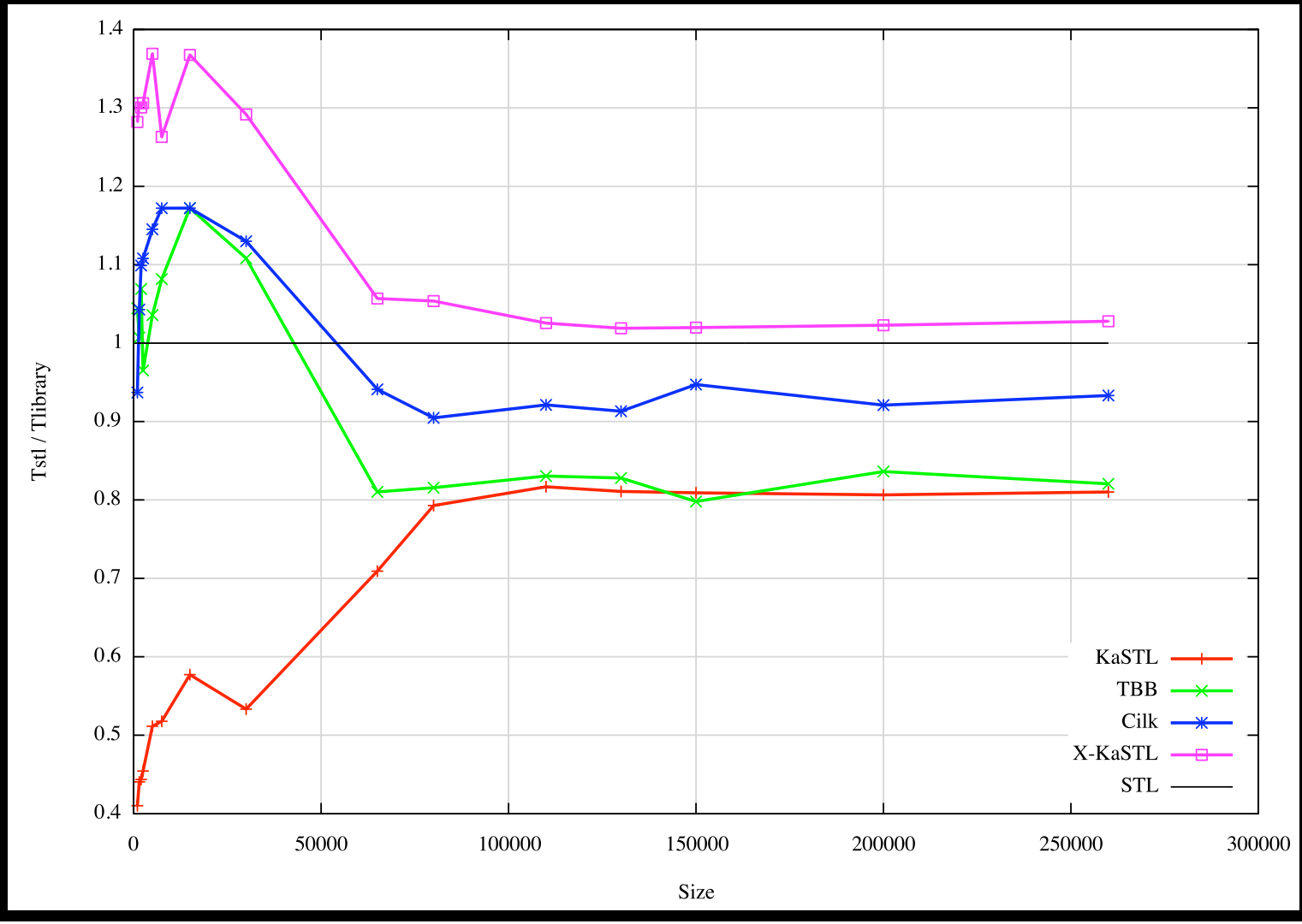
- Interest to adapt the task to activity (or idleness) of processors
- But coarse computation
  - sequential time > 0.1s

➡ + Cooperative work stealing

  - named X-KaSTL or CKaapi in diagrams

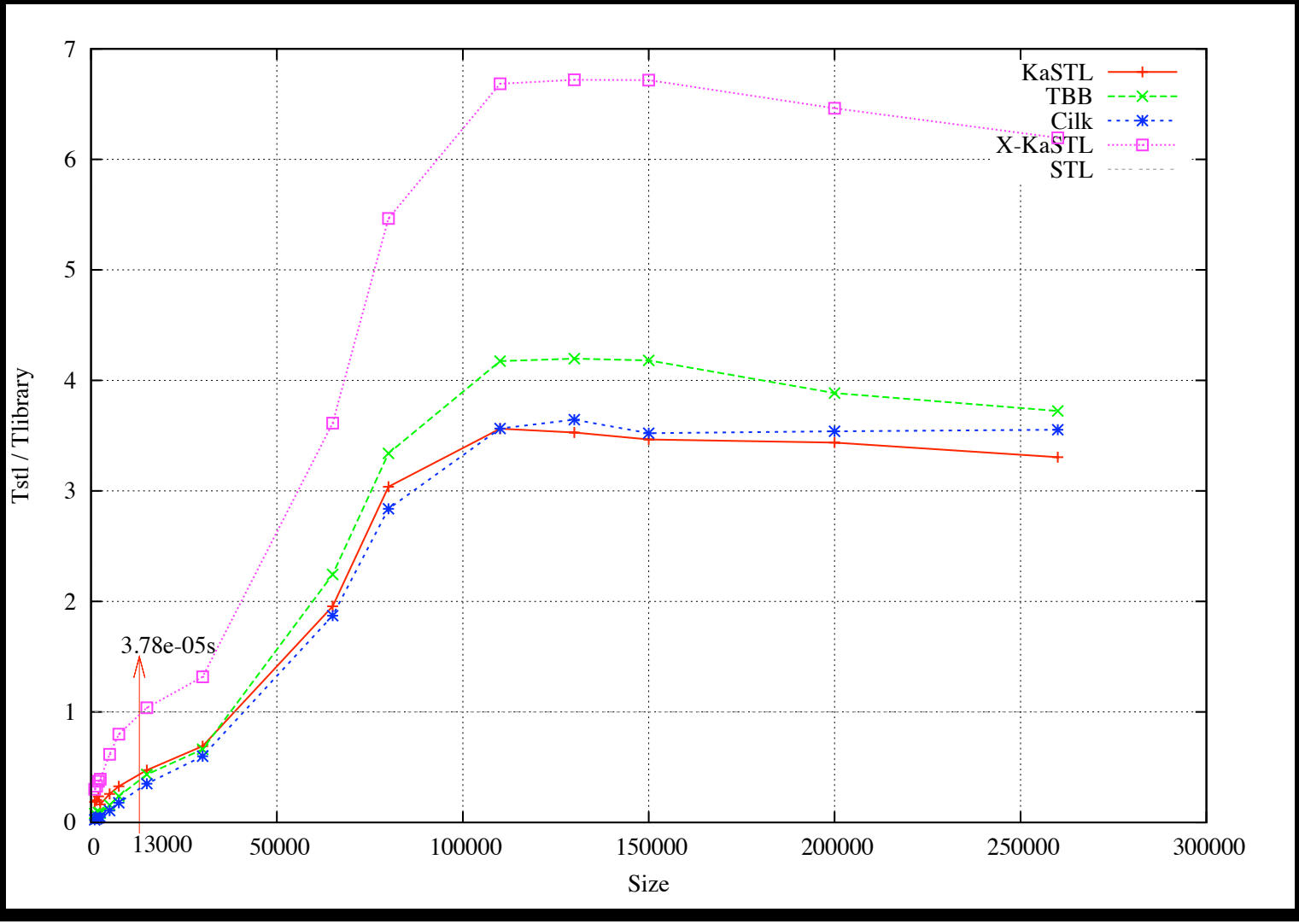
std::transform

- 1 processor



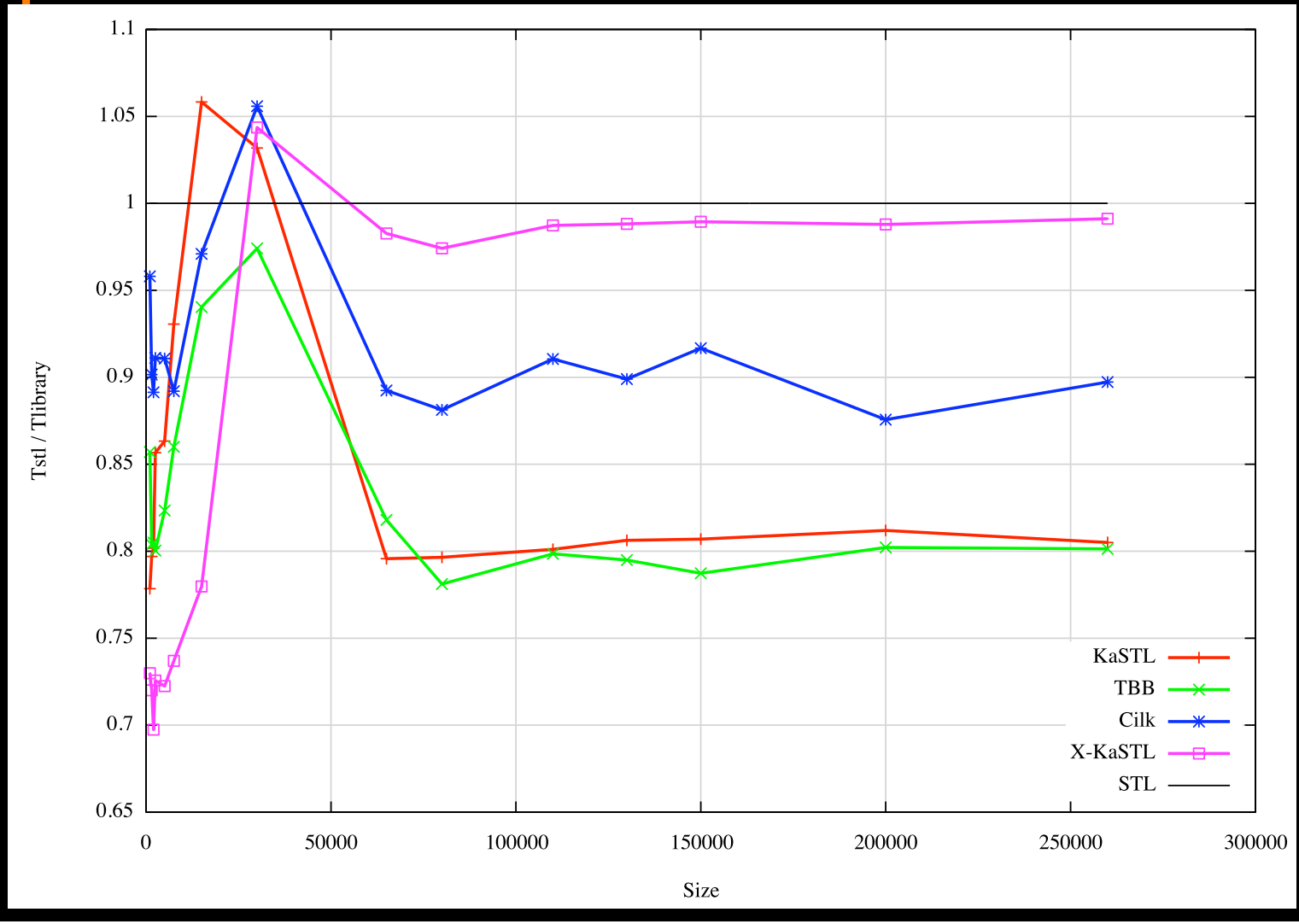
std::transform

- 8 processors NUMA machine



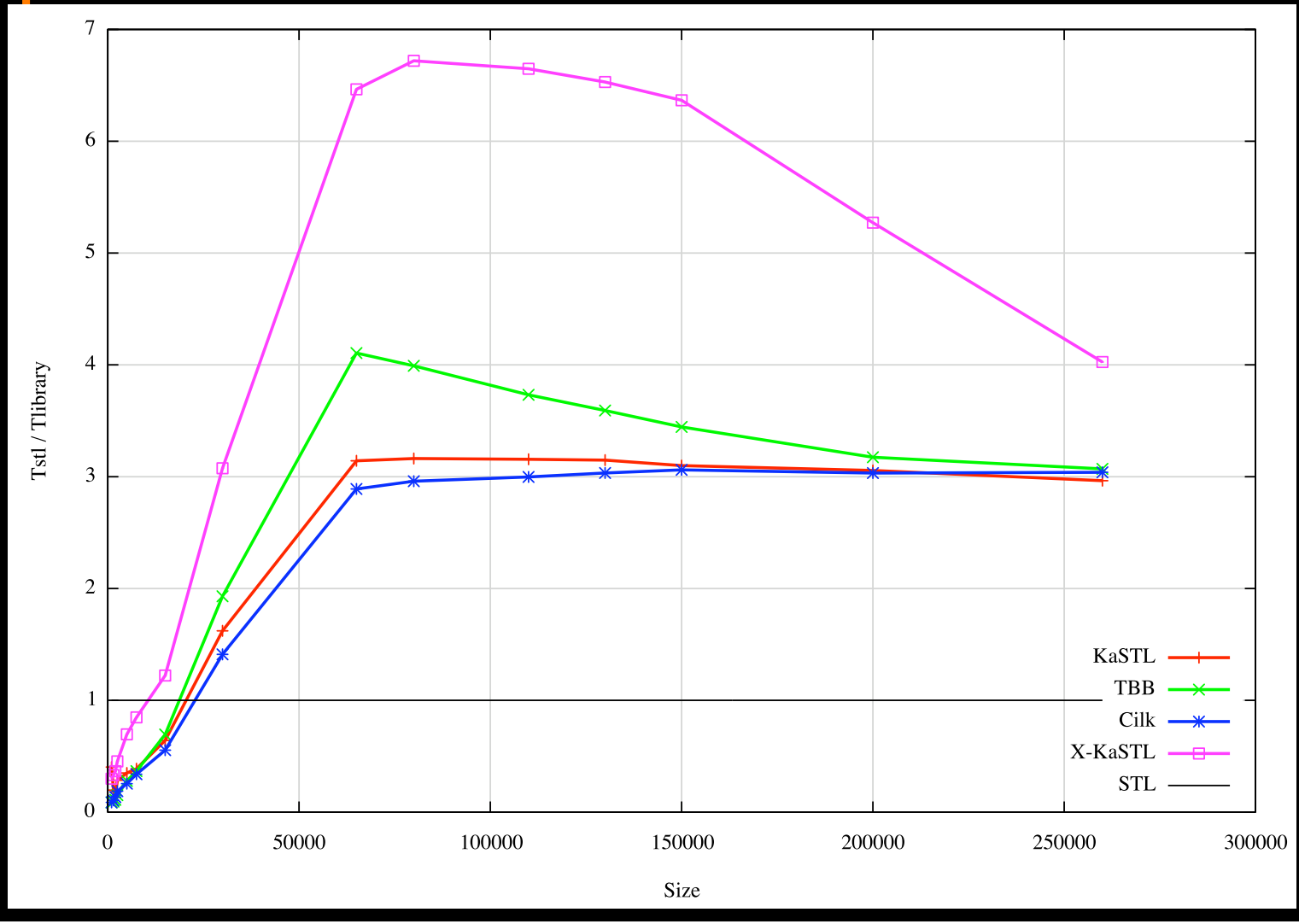
std::merge

- 1 processor



std::merge

- 8 processors



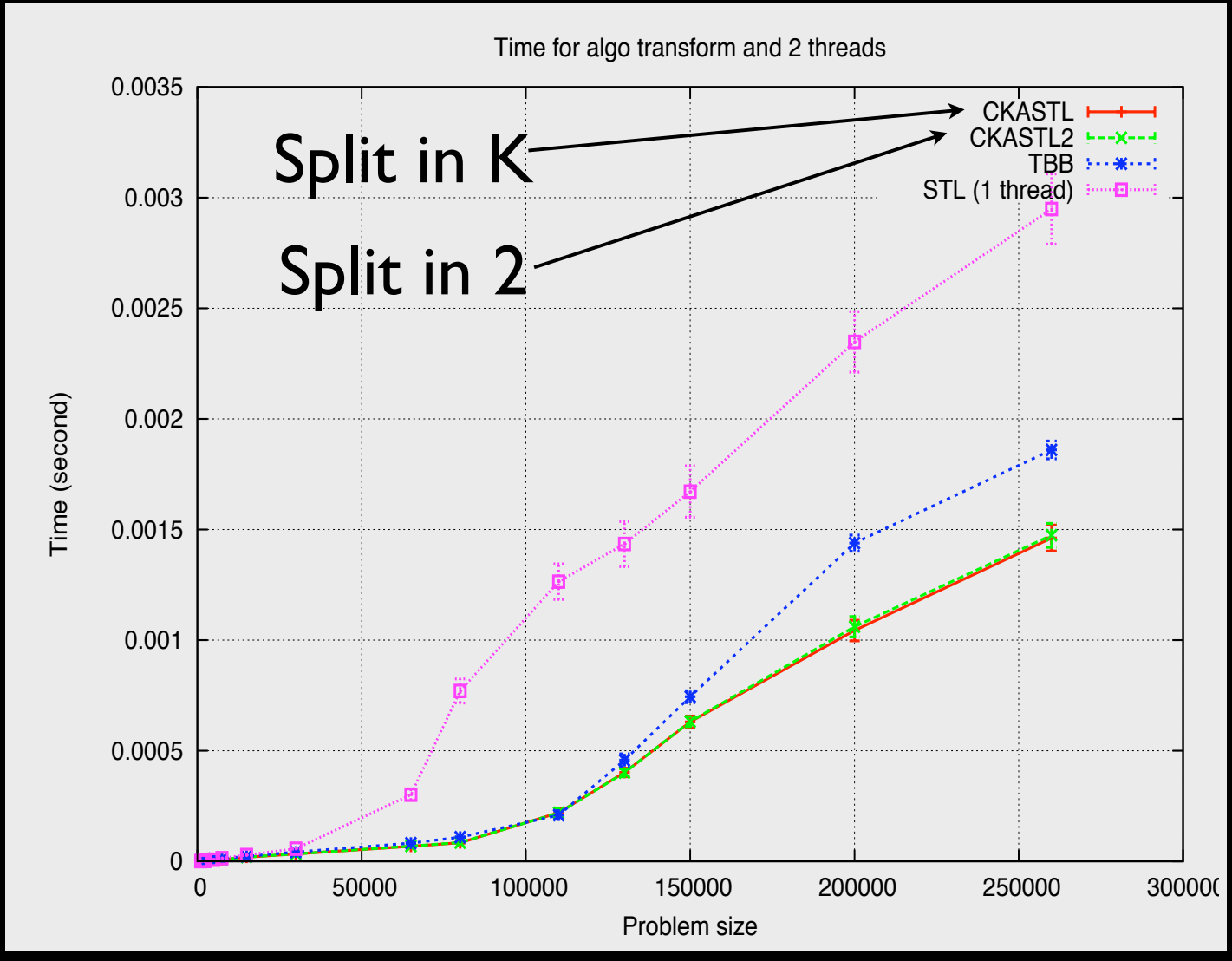
Partial conclusion

- Effective speedup at finer computation
  - sequential time ~ 10^{-3}s = 1ms

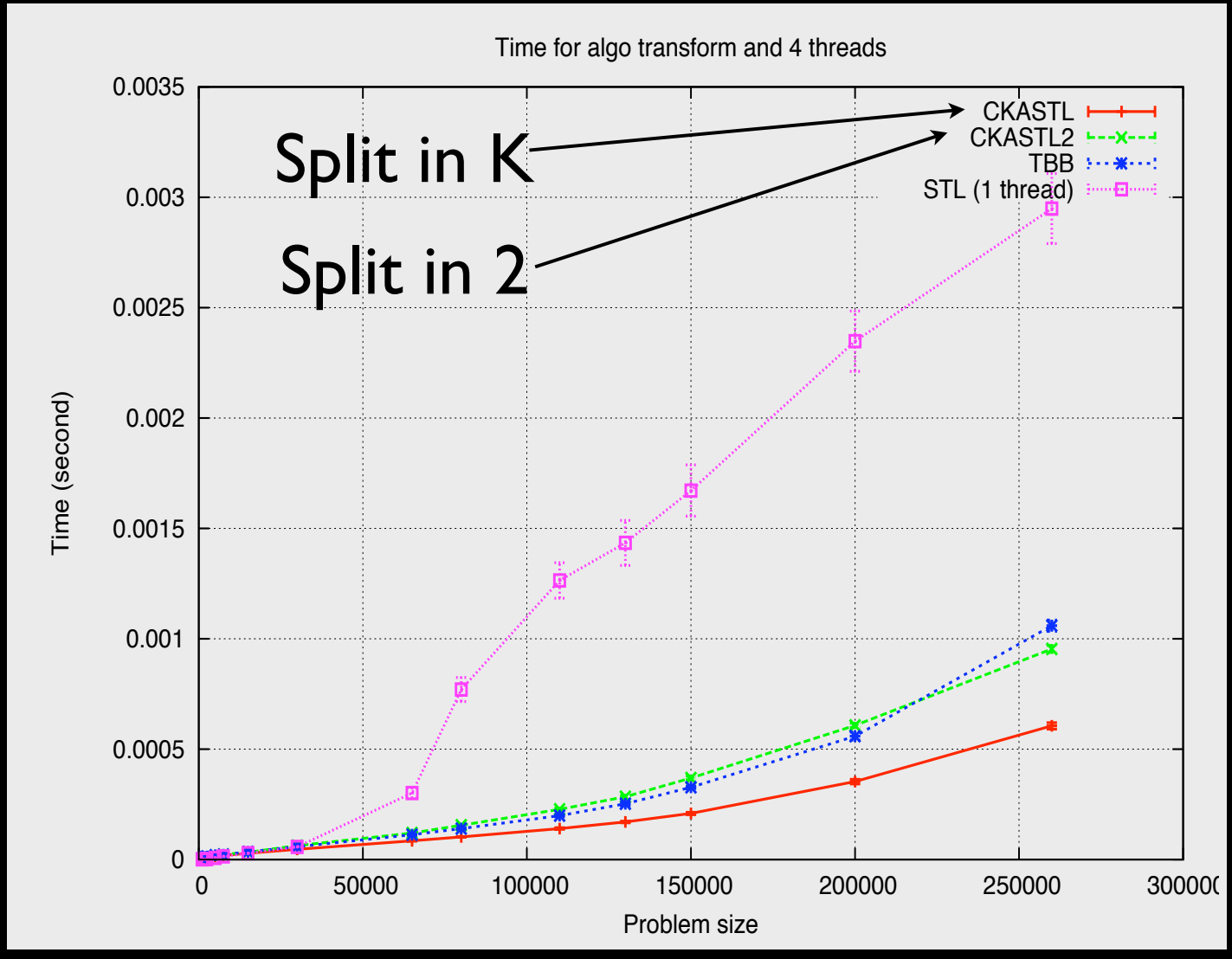
➡ impact of the better balance of work load

  - comparison split in K versus split in 2

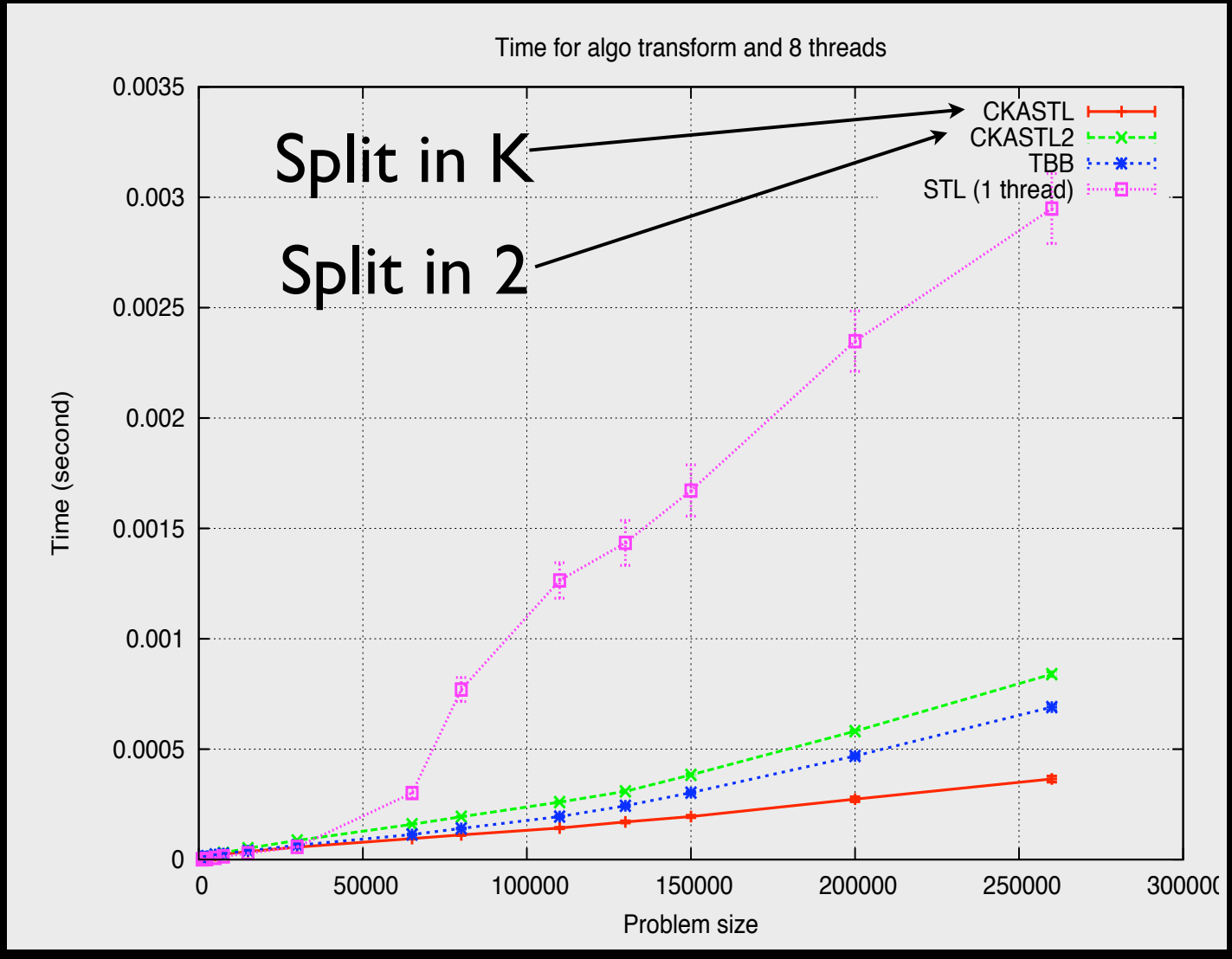
“Transform” 2 threads



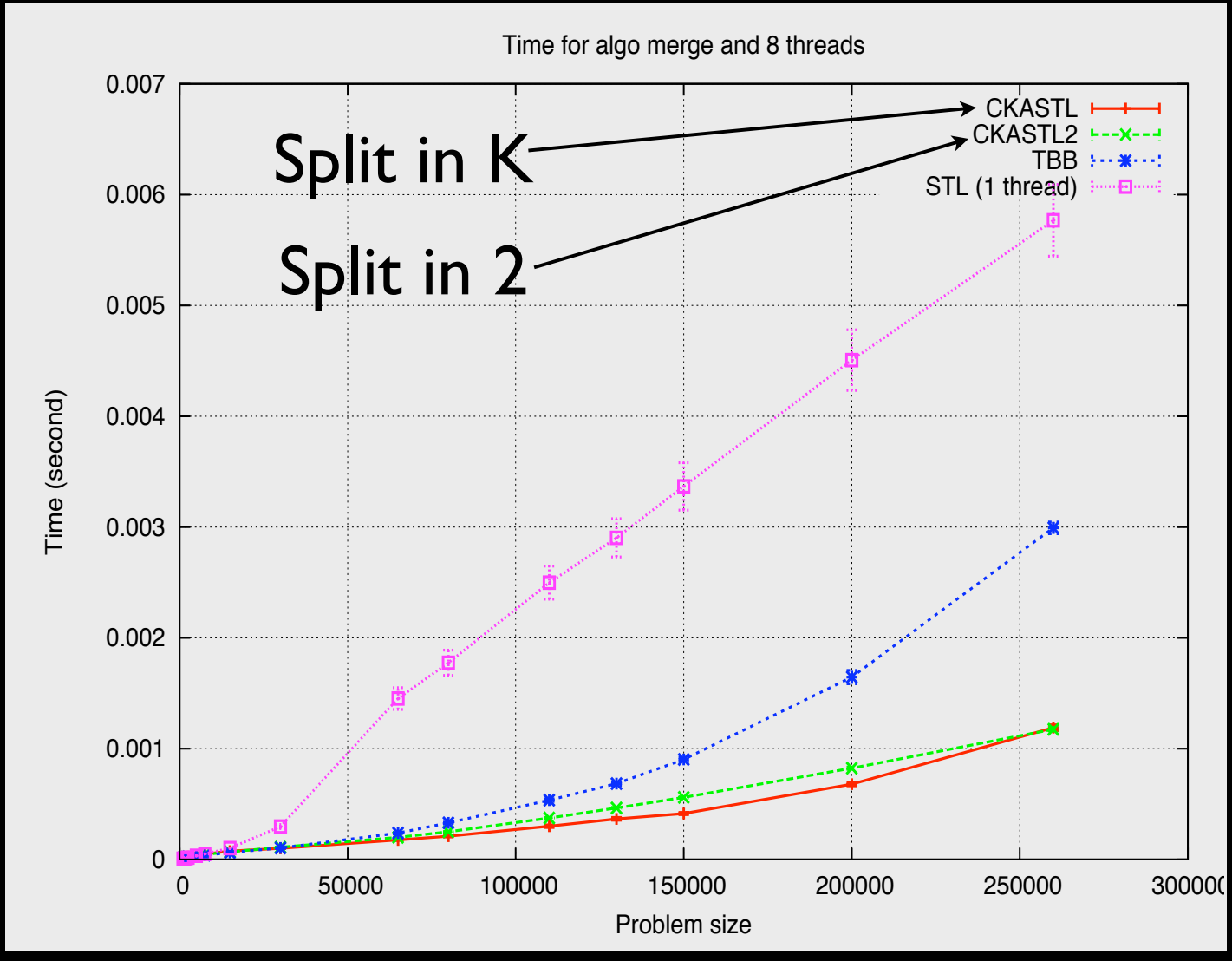
“Transform” 4 threads



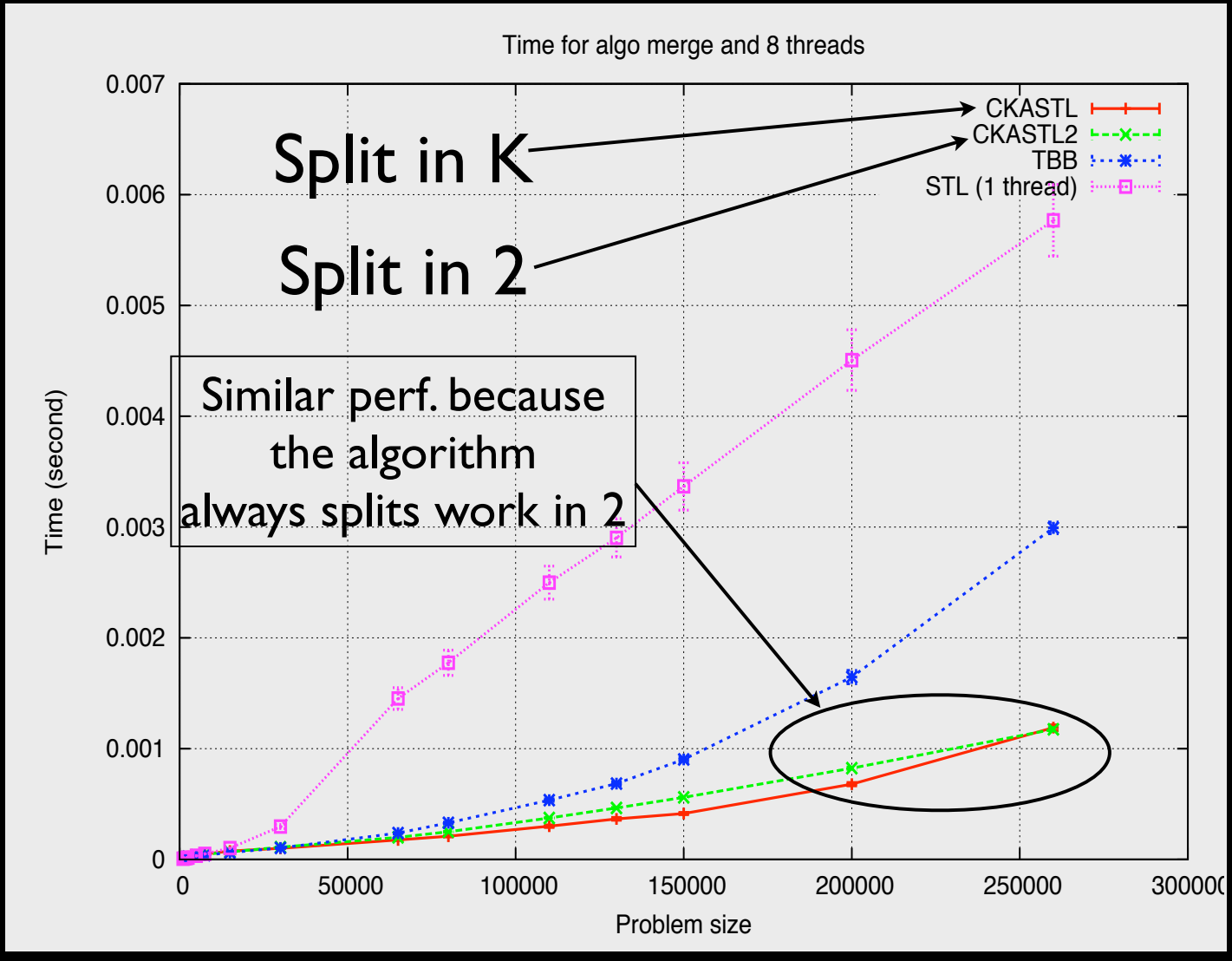
“Transform” 8 threads



“Merge”, 8 threads



“Merge”, 8 threads



Conclusion

- Athapascan/Kaapi
  - a data flow model with lazy task generation
    - reduce the work overhead
  - sequential semantics
  - original approach
  - effective parallelization of fine computation
    - with cooperative workstealing
- http://kaapi.gforge.inria.fr/

- Drawback
  - non standard research software
    - difficulty to port already parallelized applications

Perspectives

- Software being to be more robust
  - INRIA action to support development (2 years)
  - Ported on top of most Unix (Linux, MacOSX, [SunOS], iPhoneOS]
  - [2010] will be ported on IBM/BlueGene
  - [2010] will be ported on MPSoC with ST Microelectronics
- Viability of the cooperative approach
  - not yet theoretical fundation
  - coupling technics with concurrent work stealing

Perspectives

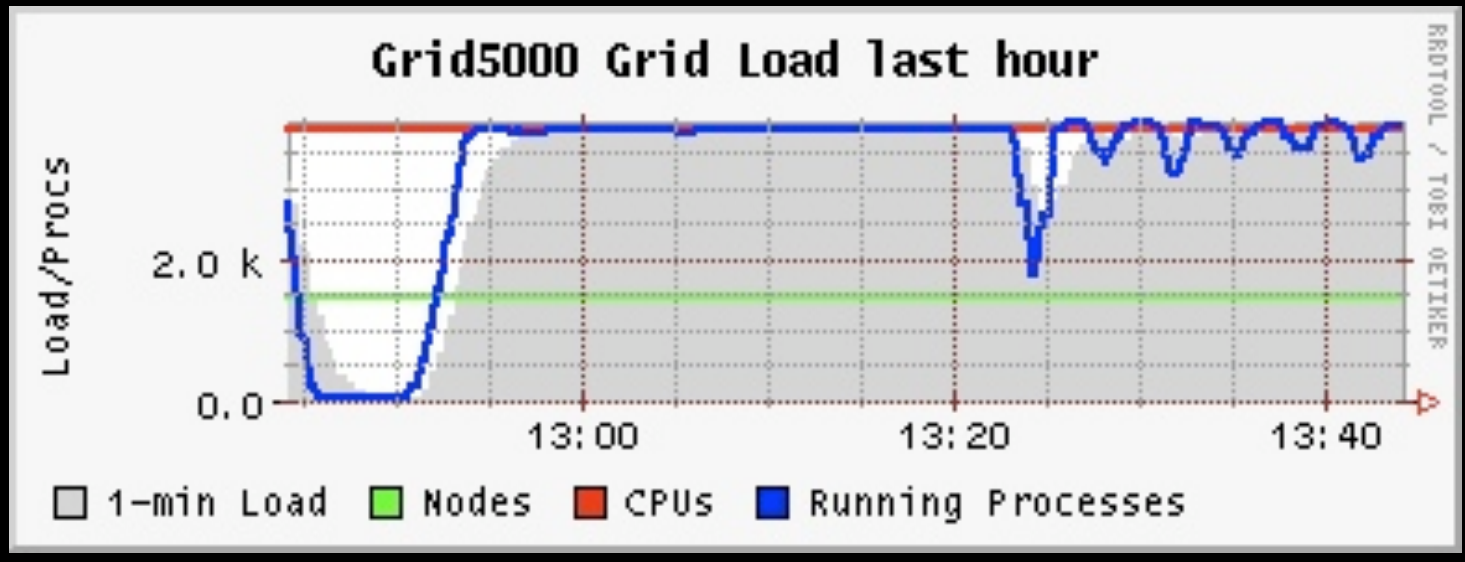
- Mixing CPUs & GPUs
  - preliminary work
  - deeper integration of the GPU as a processing resource
    - next Fermi GPU + driver ?
- Better coupling between OS & Middleware
  - importance to know (in advance) the available number of resources
- Taking into account NUMA architecture
  - ongoing work at MOAIS [JN Quintin, PhD]

Other applications

- [Parallelization of Bayesian computation]
- Parallel Computer Algebra
  - Linbox: http://www.linalg.org
- Combinatorial Opt. [PRiSM (Paris), B. Lecun]
- Academic applications
  - [III, IV, V Grid@Work contest]
    - NQueens
    - Option Pricing application based on Monte Carlo Simulation
  - Numerical kernel for CEM, CFD Grid application
    - Finite difference / Finite element
  - Reaction / diffusion with Chemical species
    - Finite difference
- SOFA (http://www-sofa-framework.org)

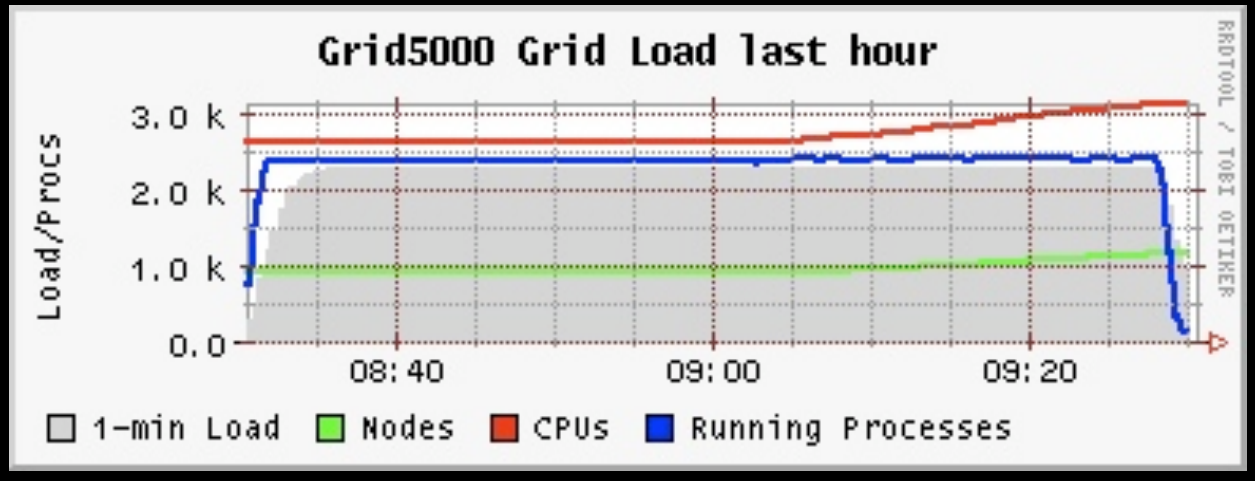

KAAPI

NQueens [2006,2007]



- Grid5000 (French academic national grid)
  - 2006: N=23 in 74min on 1422 cores
  - 2007: N=23 in 35mn 7s on 3654 cores
- Taktuk: fast deployment tool

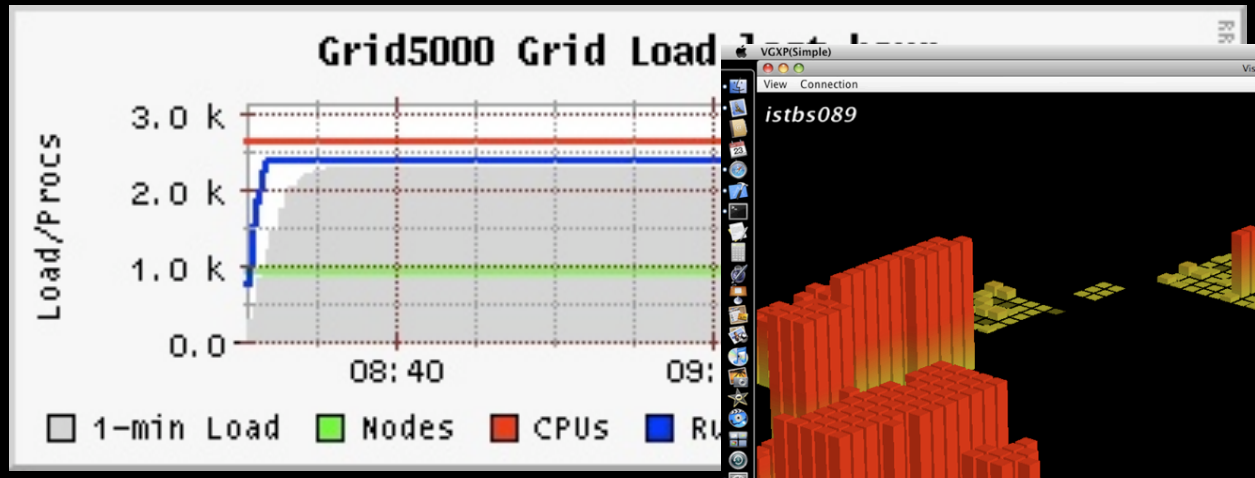
Monte Carlo / Option Pricing



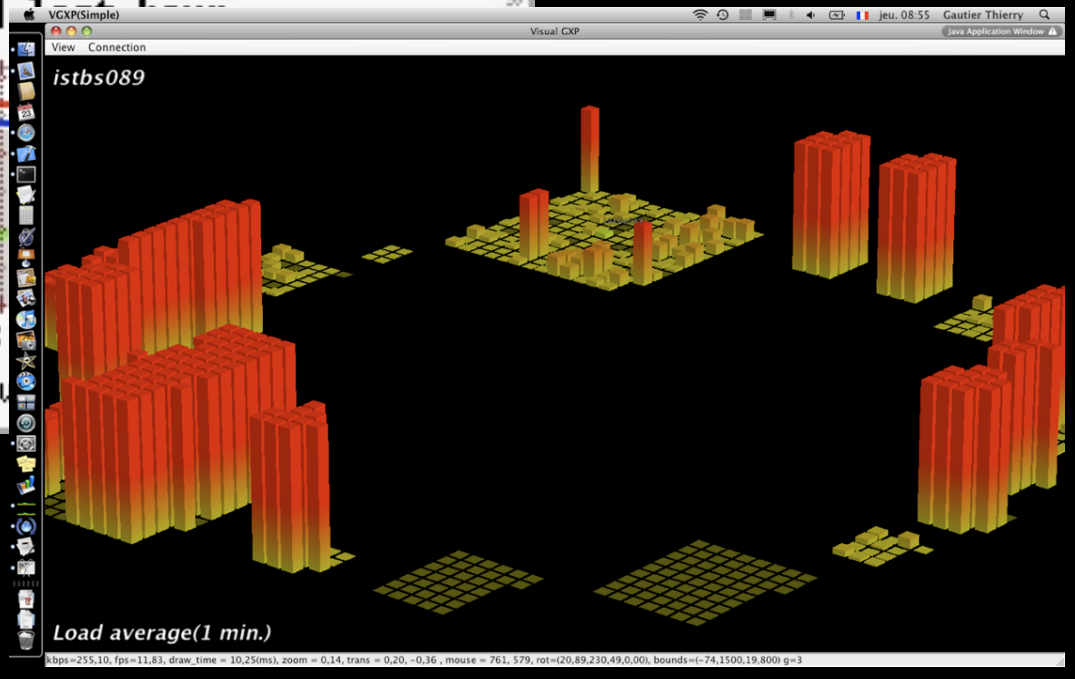
Grid5000: France

- 3609 cores: ~2700 Grid5000 ~900 Intrigger
- SSH connection between Japan-France

Monte Carlo / Option Pricing



Grid5000: France



Intrigger: Japan

- 3609 cores: ~2700 Grid5000 ~900 Intrigger
- SSH connection between Japan–France

Physics Simulation

- SOFA: real-time physics engine
- Strongly supported INRIA initiative
- Open Source:

  http://www.sofa-framework.org
- Target application:

  Surgery simulation

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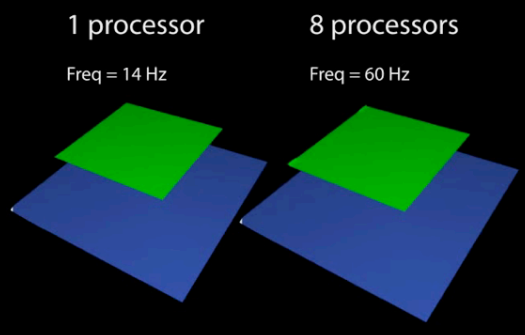

Physics Simulation

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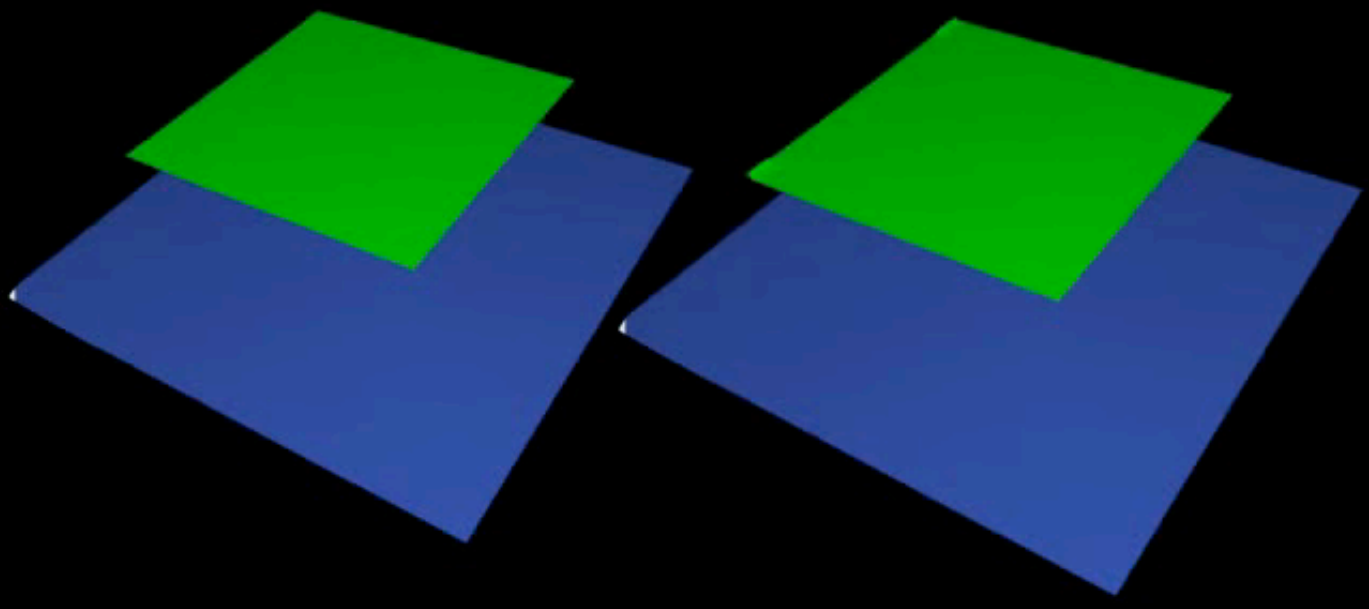
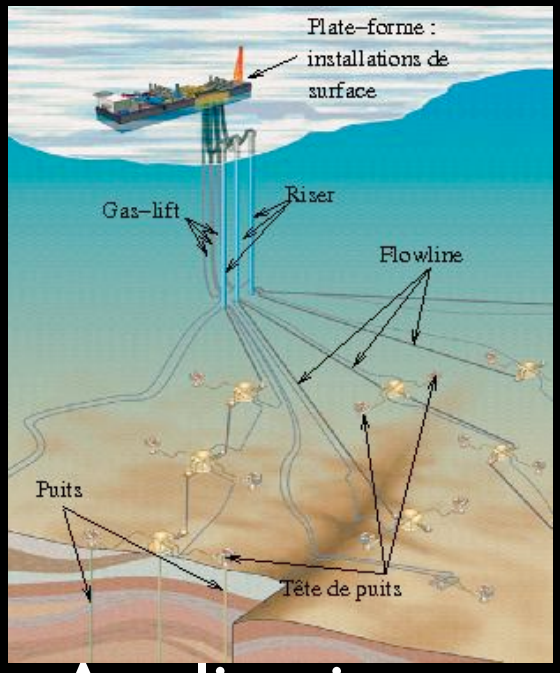
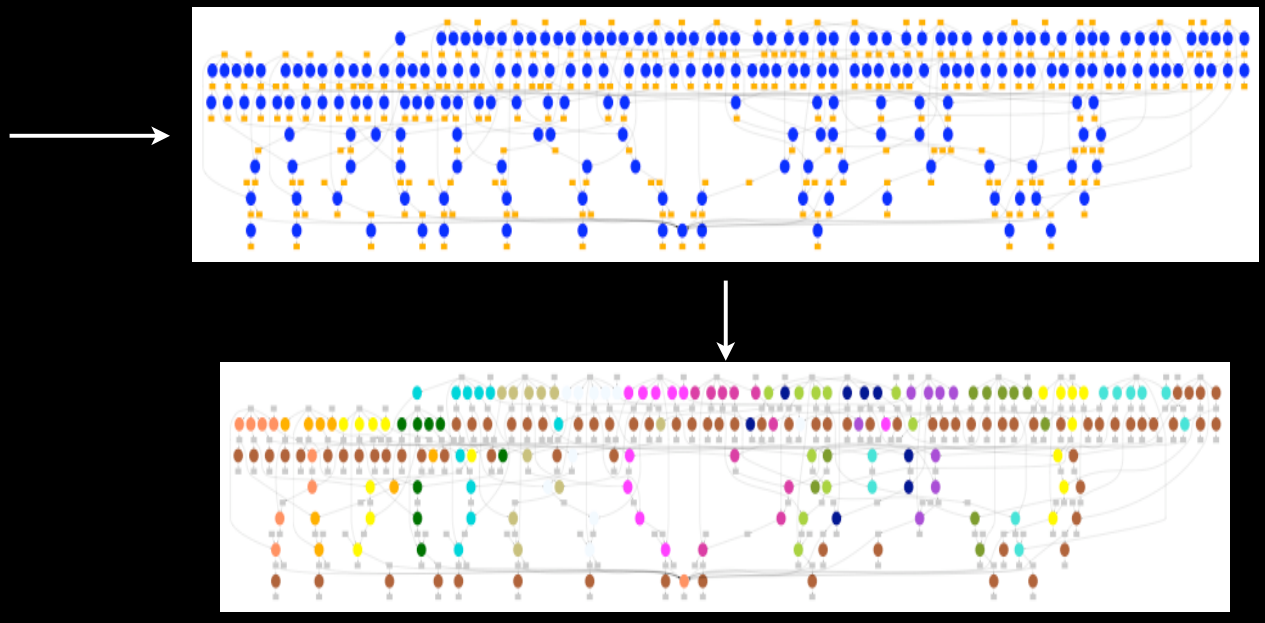


Iterative Application

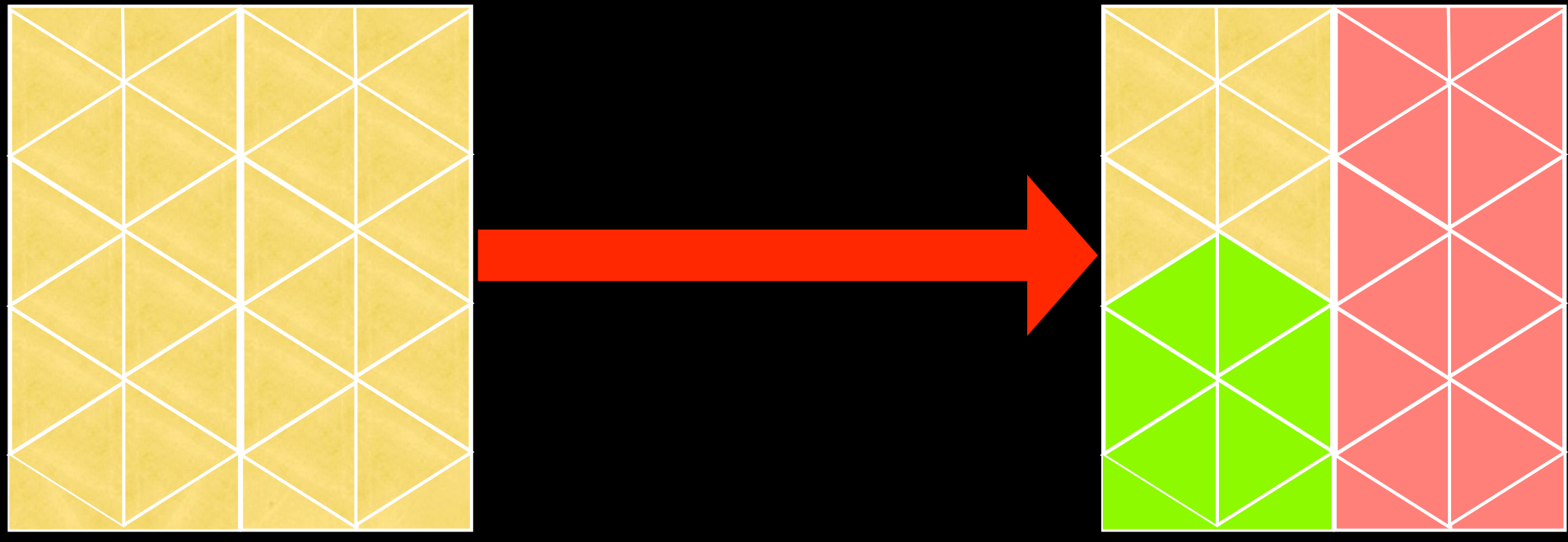
- Scheduling by graph partitioning
  - Metis / Scotch

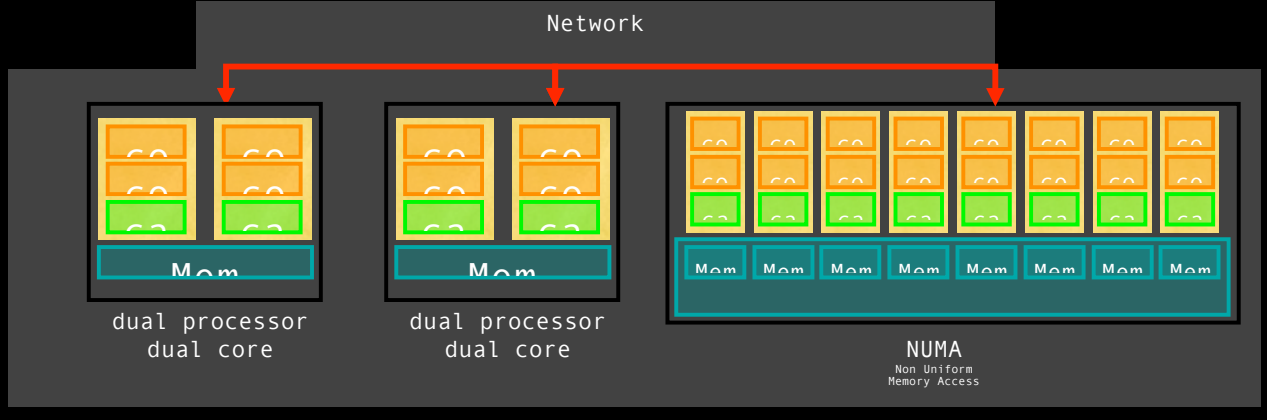


Application



Domain decomposition





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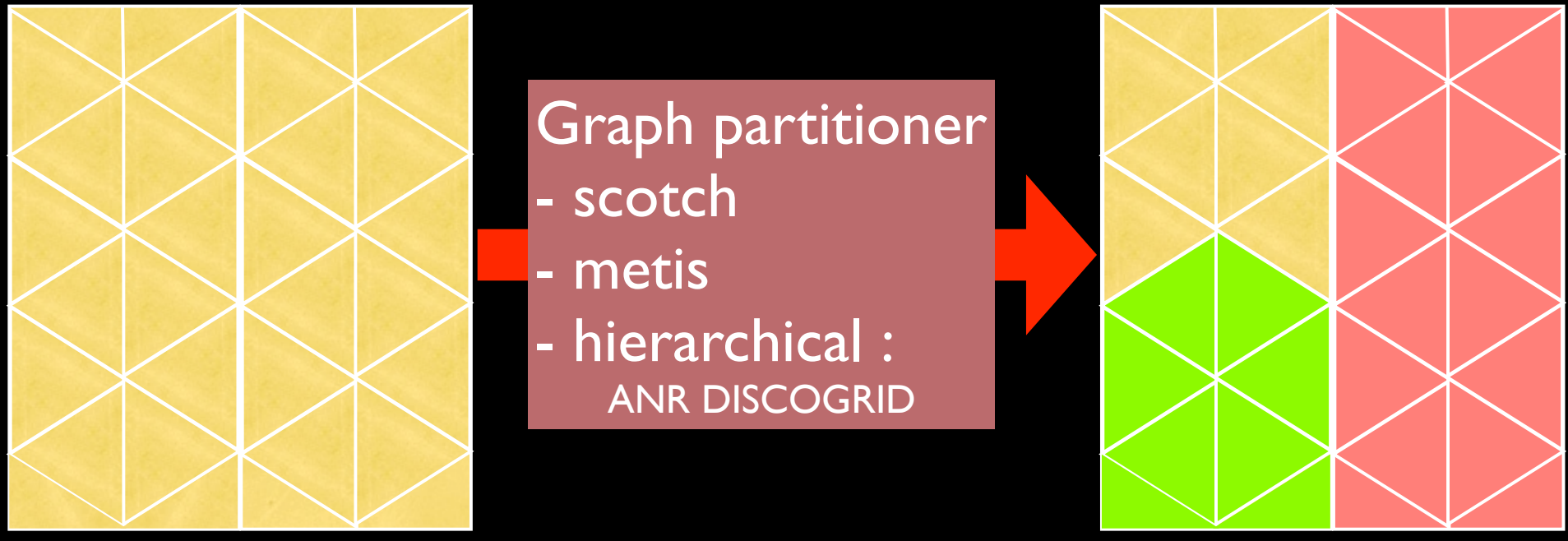
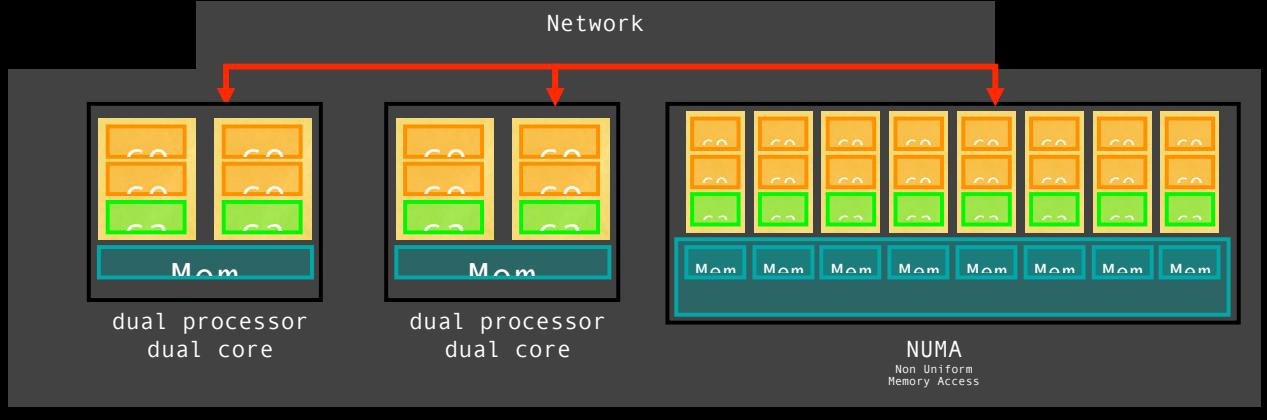




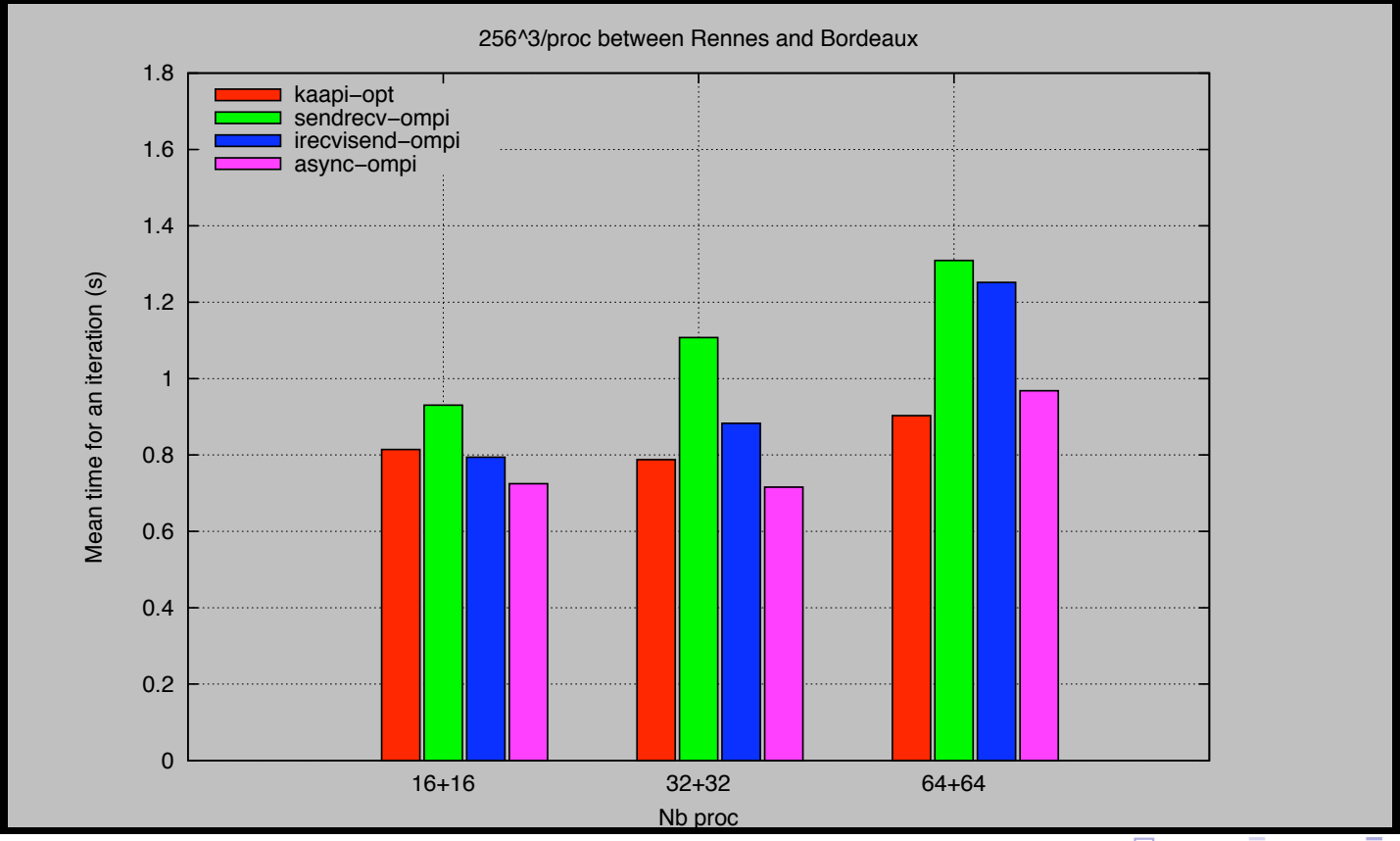
Experiments

- **Finite Difference Kernel**
  - Kaapi / C++ code versus Fortran MPI code
  - Constant size sub domain D per processor
  - Cluster : N processors on a cluster
  - Grid : N/4 processors per cluster, 4 clusters

D=256^3	# processors	Cluster (s)	Grid (s)	Overhead
KAAPI	1	0.49	0.49	-
	64	0.55	0.84	0,53
	128	0.65	0.91	0,4
MPI	1	0.44	0.44	-
	64	0.66	2.02	2,06
	128	0.68	1.57	1,31

Optimizing MPI code

- **Overlapping communication by computation**
  - At the cost of important code restructuring



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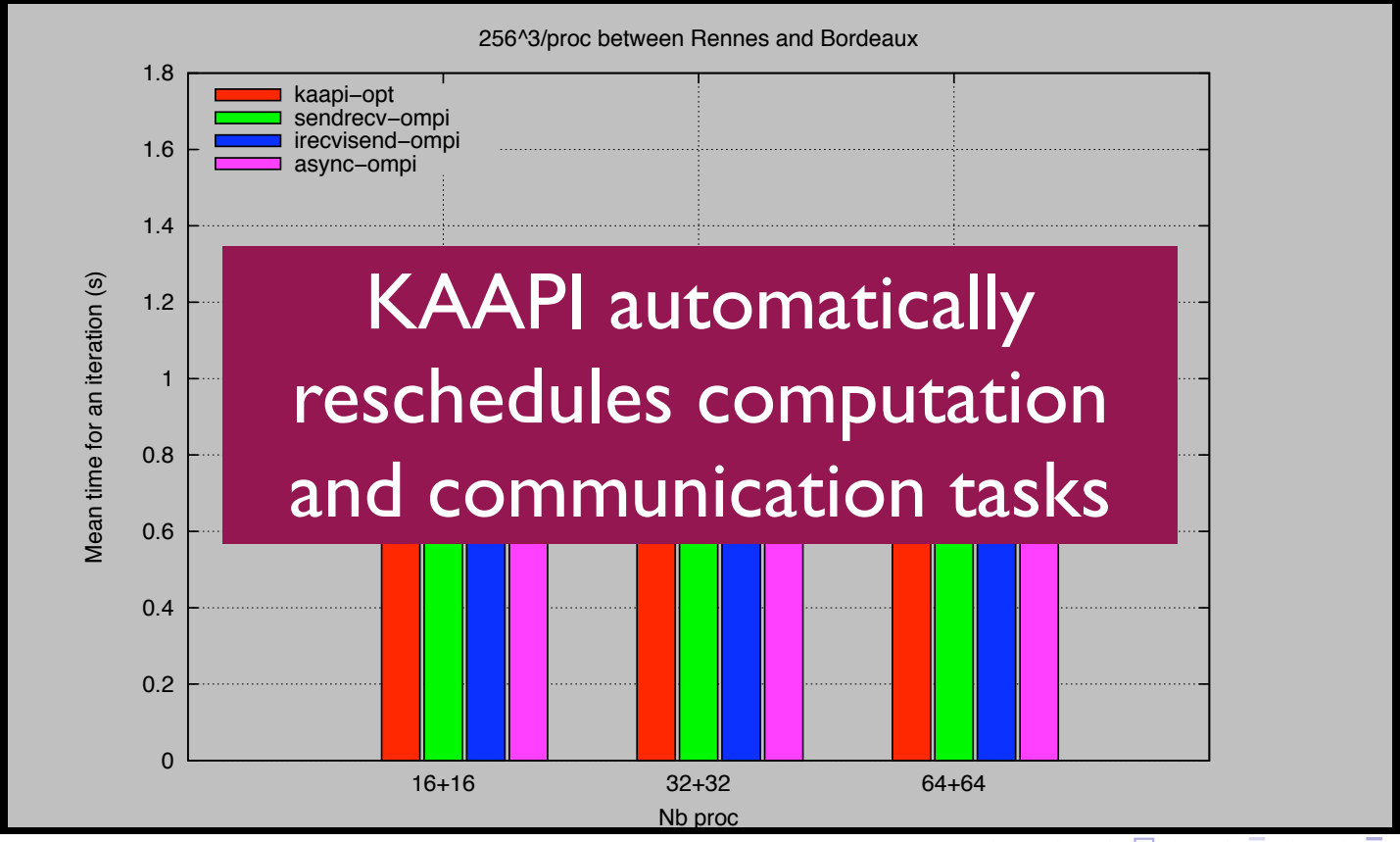

Communication

- Active message like communication protocol
- Multi-network (TCP, Myrinet, ssh tunnel with TakTuk)
- High capacity to overlap communication by computations
- Original message aggregation protocol


KAAPI