Pushing the limits of work-stealing

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Authors

- Senior developer for Intel® Threading Building Blocks (Intel® TBB), since 2006, before the first Beta release
- Patent applications for algorithms of concurrent_hash_map and auto partitioner
- Currently responsible for Intel TBB task scheduler functionality and improvements for OpenCL* runtime team.
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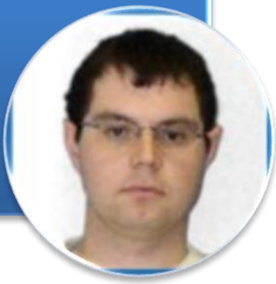
Anton Malakhov

- Lead developer of OpenCL* runtime for CPU and Intel® Many Integrated Core Architecture (Intel® MIC Architecture) since first line was added
- Currently main focal point between Intel's OpenCL and Intel TBB teams, closely working with Intel TBB team on definition, prototyping and deployment of new features

Evgeny Fiksman



Background

Intel® Xeon Phi™ coprocessor

- Intel® Many Integrated Core Architecture
- ~60 cores / ~240 threads
- Wide SIMD

OpenCL

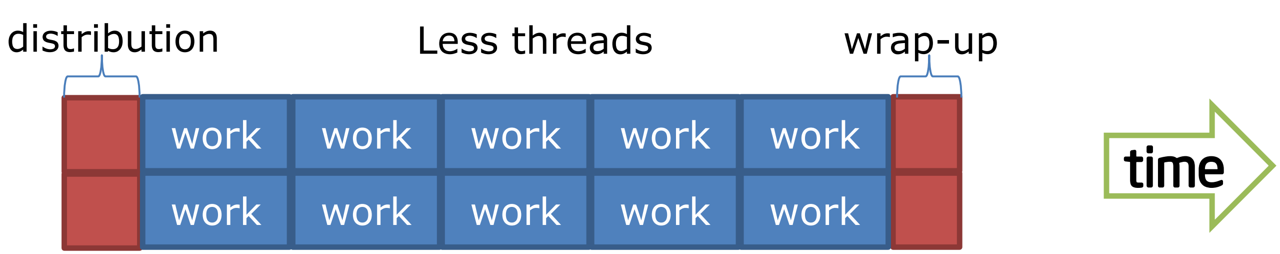
- Heterogeneous parallel programing on CPU, GPGPU, accelerators
- Host / Device model, C99 based
- Cross-platform, functional portability
- Challenge: Performance portability

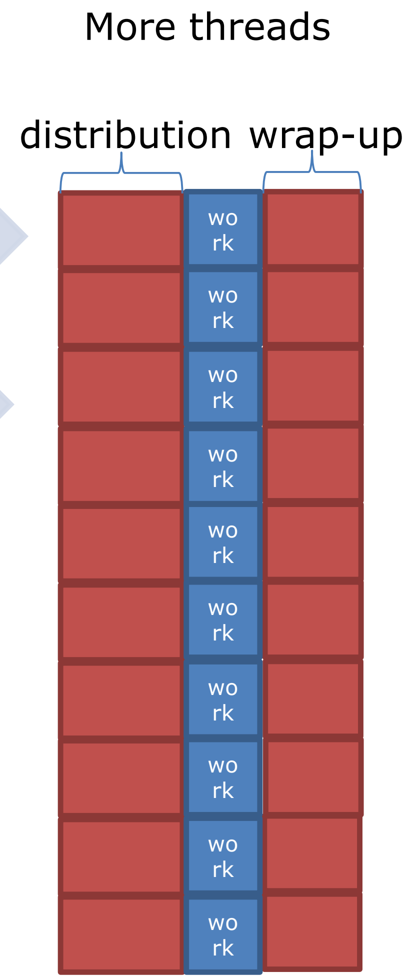
Intel TBB

- Work-stealing scheduler
- Efficient load balancing
- Nested parallelism
- Containers, algorithms, locks…
- www.threadingbuildingblocks.org

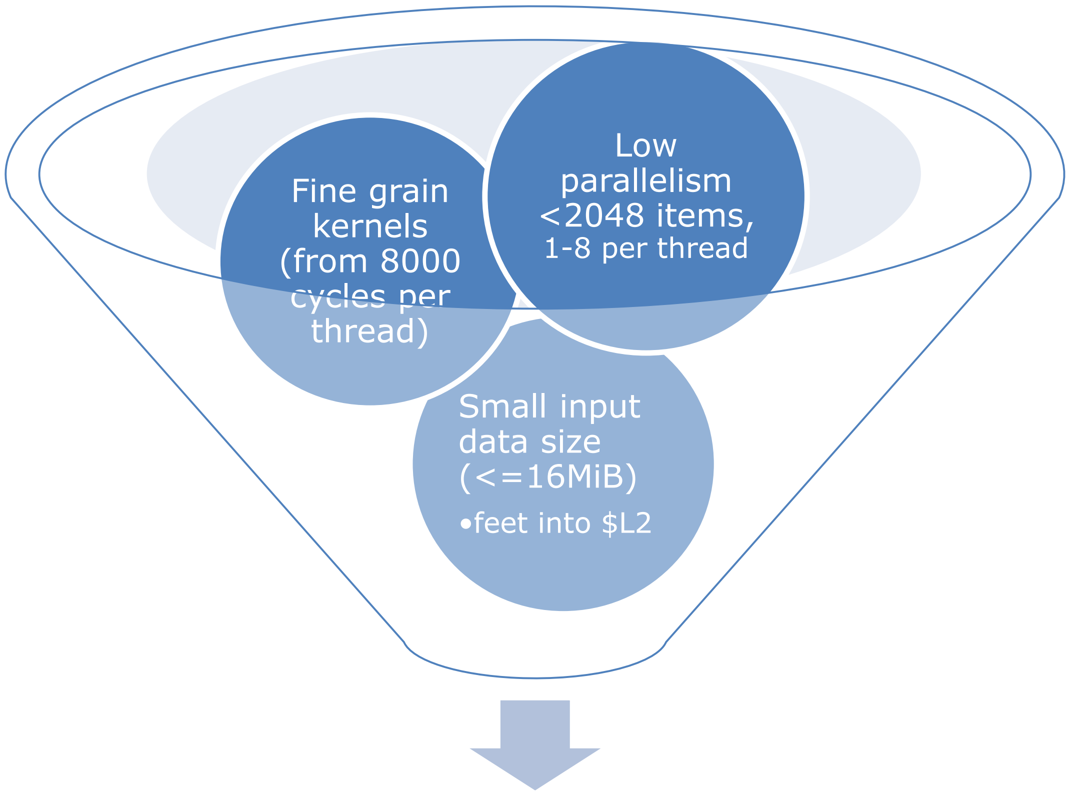
OpenCL on Intel Xeon Phi coprocessor: challenges

- **GPGPU applications** → Short/Lightweight kernels → Memory Bounded
- **Latency** → Host-Device communication → Memory Transfer and Compute overlap
- **Throughput** → Increased synchronization overheads → High memory latency → Need efficient threading
- **Intel MIC architecture** → More threads → Wider SIMD size → Increased overheads





Target Benchmark's Characteristics



Native C++ reproducers on top of OpenMP* API and Intel TBB

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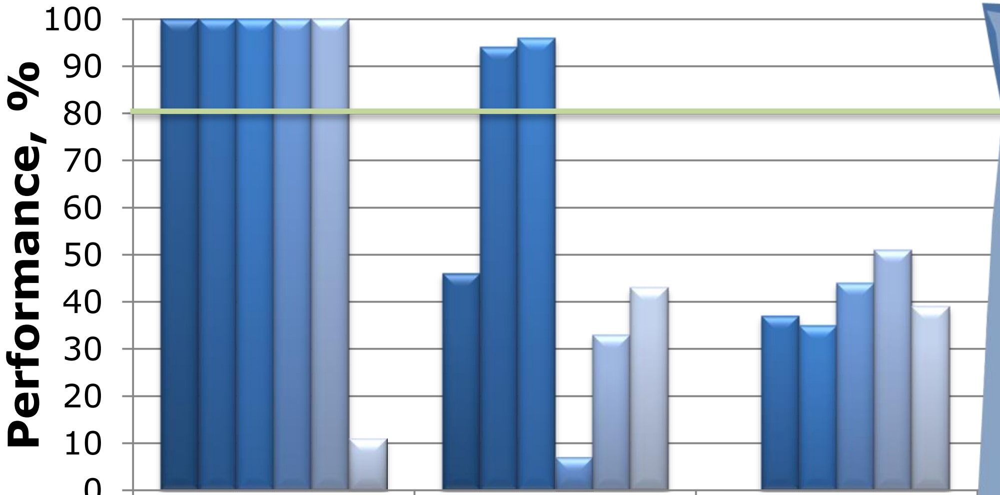
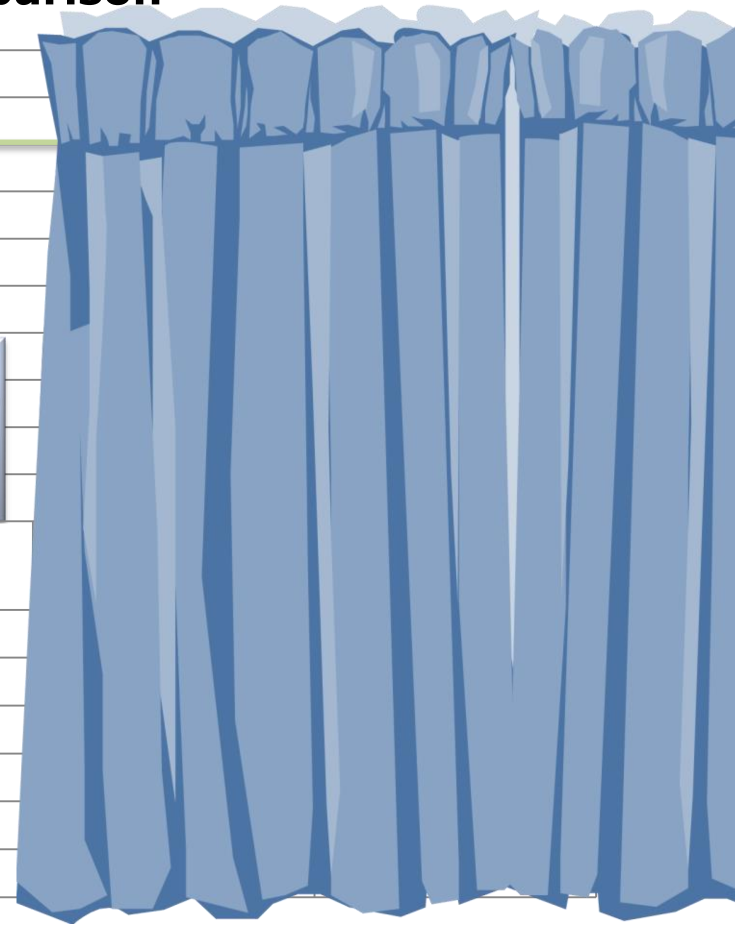
Initial results

Normalized performance comparison





Threading: Benchmarks	omp static	omp dynamic	TBB 4.1 defaults
minimal	100	46	0
conformance	100	94	37
reduction	100	96	35
scan	100	7	44
spmv	100	33	51
spmv-unbalanced	11	43	39

Configuration Info - SW Versions: Intel® C++ Intel® 64 Compiler, Version 13.1.1.163; Hardware: Intel® Xeon Phi™ Coprocessor 7120 (16GB, 1.238 GHz, 61C/244T); MPSS Version: 3.1; Flash Version: 2.1.03.0386; Host: 2x Intel® Xeon® CPU E5-2680 0 @ 2.70GHz (16C/32T); 64GB Main Memory; OS: Red Hat Enterprise Linux Server release 6.2 (Santiago), kernel 2.6.32-220.el6.x86_64; Benchmarks are measured only on Intel® Xeon Phi™ Coprocessor with power management disabled.
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General optimizations

Improve inter-core communication

- Tuning pause times for spin-loops
- Optimized memory layouts for less shared cache
- Manual cache prefetching and eviction

Overcome multi-core overheads

- Reduce thieves contention on a victim
- Reduce synchronization points on critical path
- Pin worker threads to remove outliers

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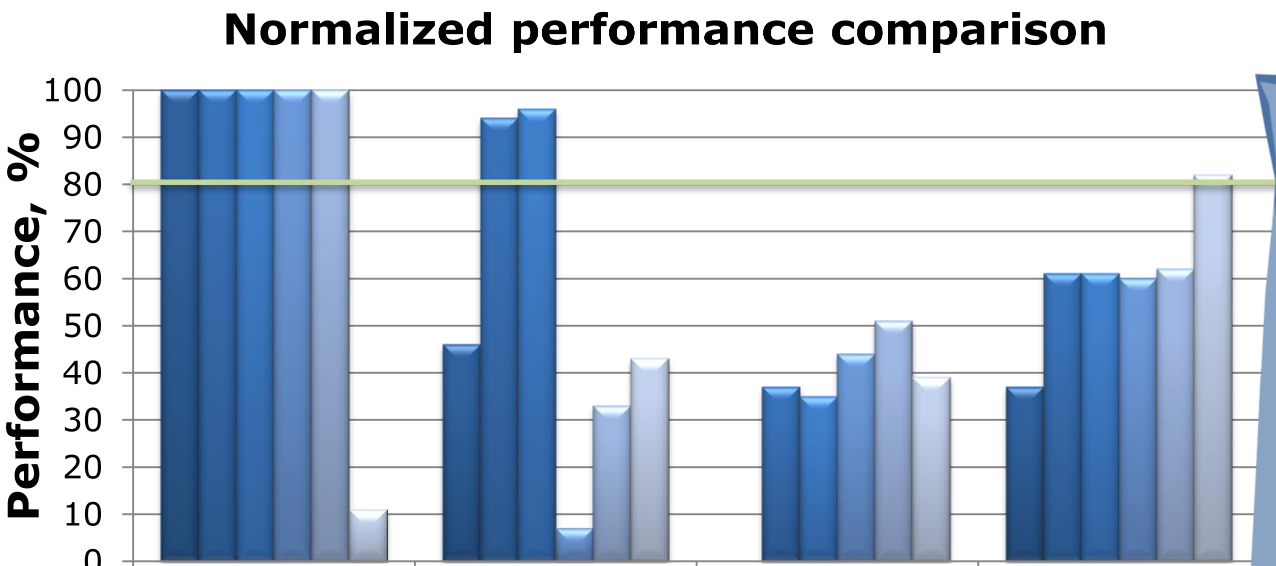
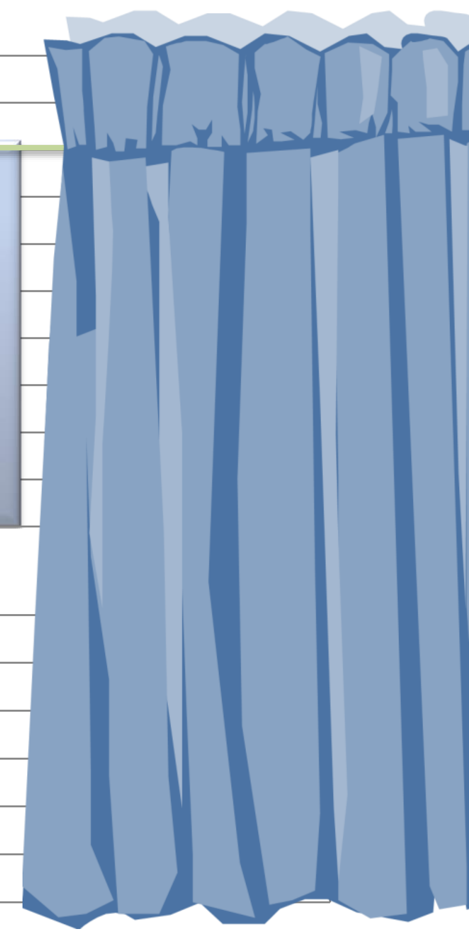
Intermediate results



Threading: / Benchmarks	omp static	omp dynamic	TBB 4.1 defaults	TBB 4.2 U2 defaults
minimal	100	46	0	37
conformance	100	94	37	61
reduction	100	96	35	61
scan	100	7	44	60
spmv	100	33	51	62
spmv-unbalanced	11	43	39	82



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Load balancing challenge

OpenMP* static schedule shines on well balanced work

- ✔ No load-balancing overheads, work is distributed equally across threads
- ✔ Deterministic distribution: cache locality on repeating workloads

↓

OpenCL needs load balancing without killing performance
Work-stealing works against things which help OpenMP* shine

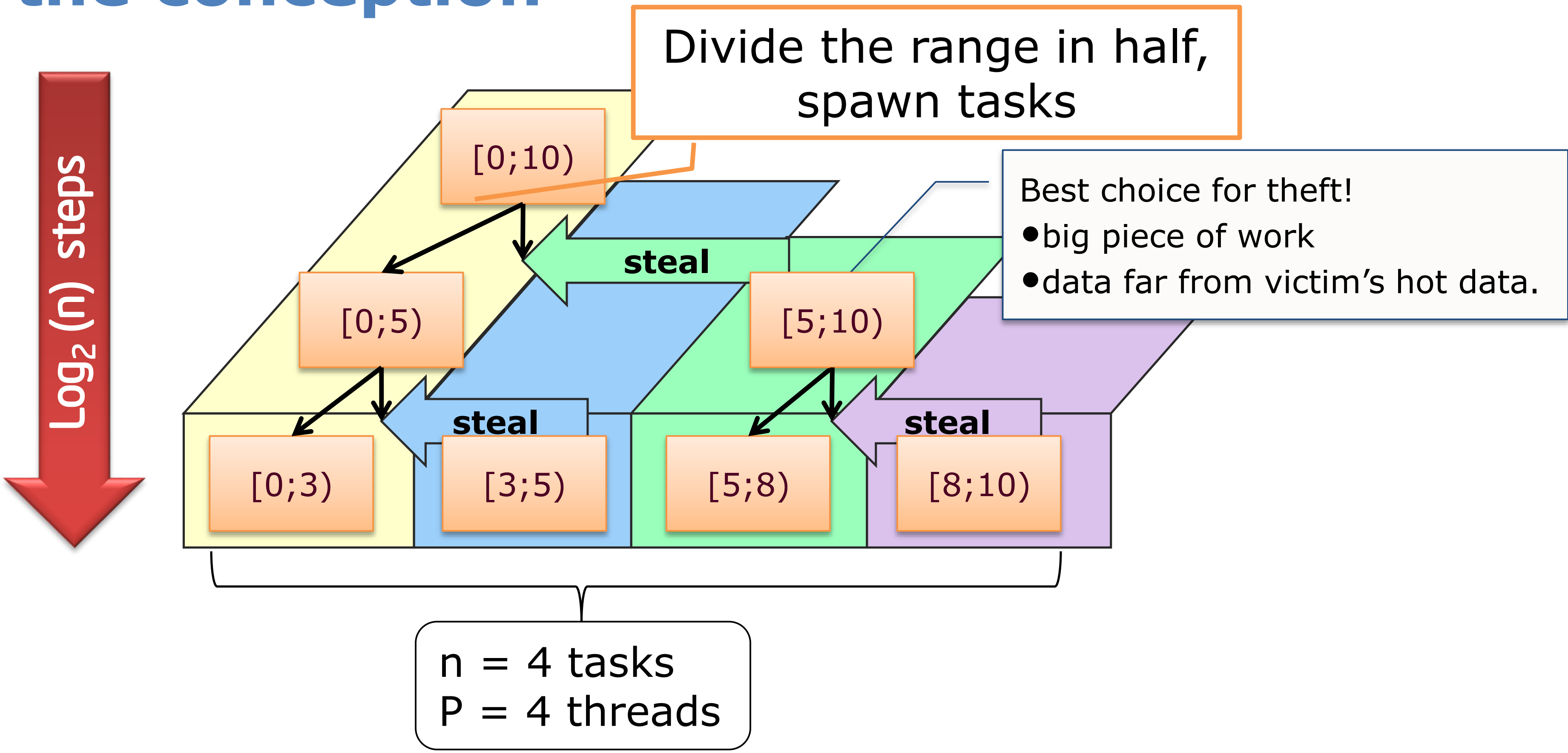
- ⊘ TBB assigns work to threads unevenly, Load-balancing breaks equal distribution
- ⊘ Random work-stealing disrupts cache locality

↓

One-fits-all approach needed

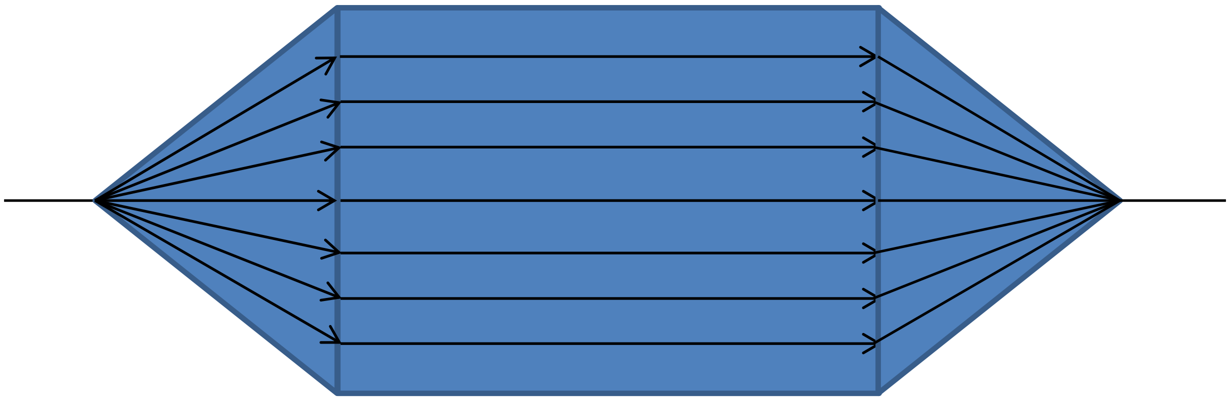
20% behind omp static is tolerable

Work distribution through stealing: the conception



Stealing is random → any thread can steal from any other thread → Non-determinism. Slow for few tasks across lots of threads

Our work distribution issues



Distribution

- Non-determinism →cache locality
- Slow for first and last tasks
- Irregularity →final imbalance

Executing

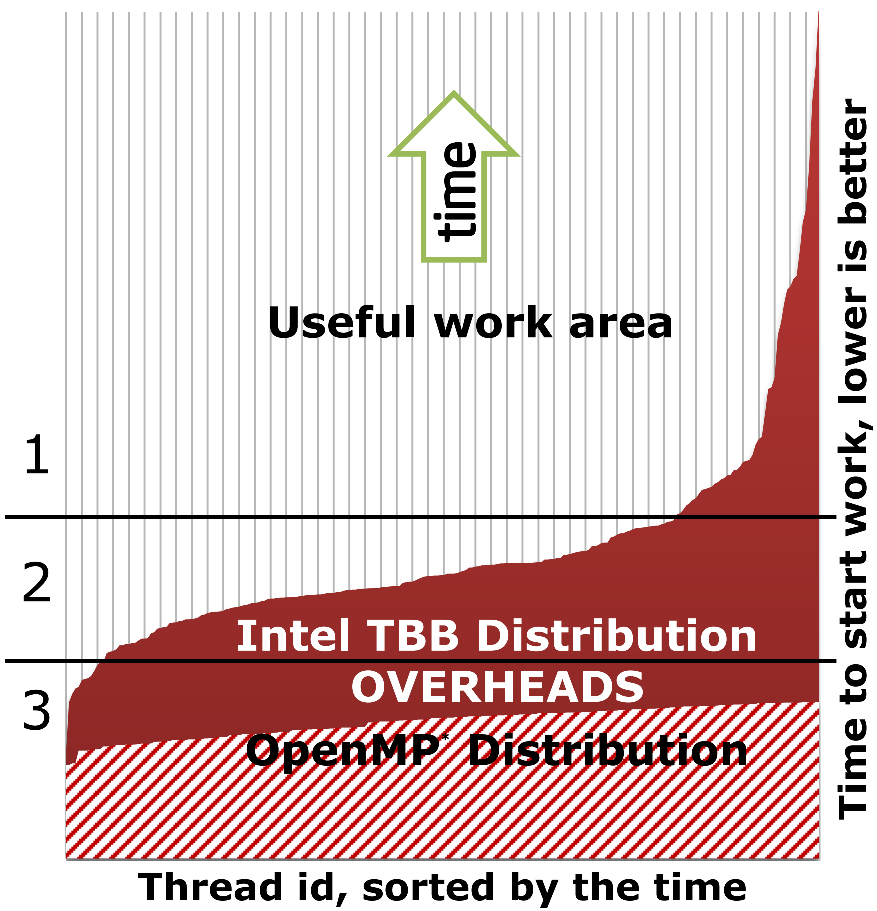
- Cache locality
- Granularity

Final load balancing

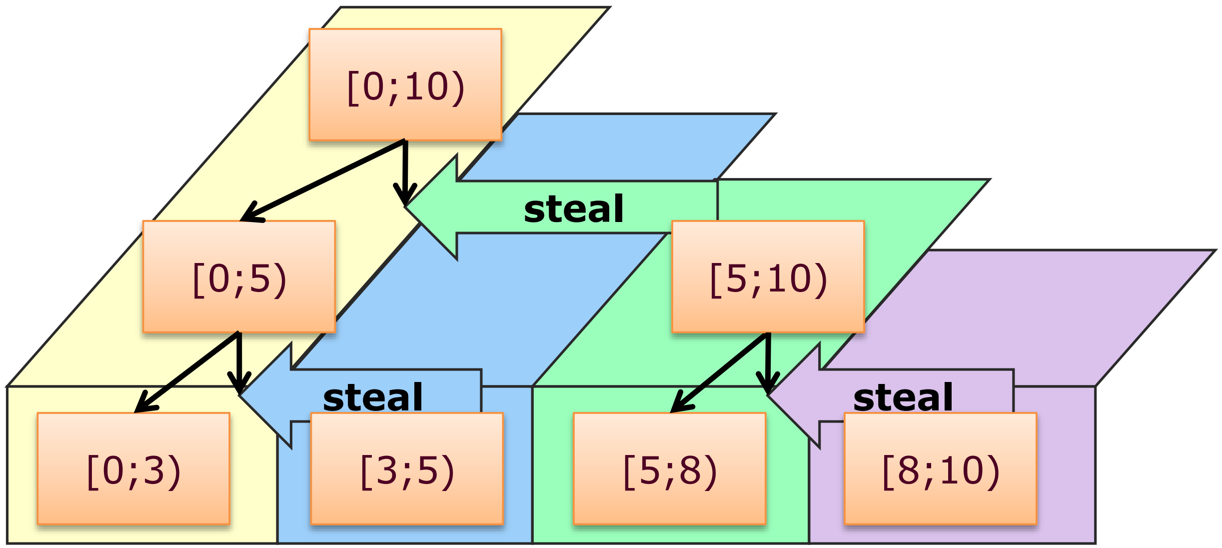
- Irregularity induced imbalance
- Or caused by too small granularity

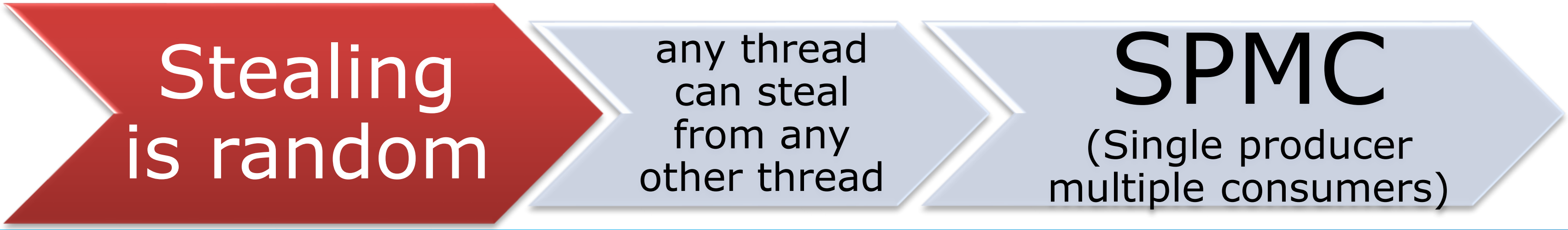
Work distribution through stealing: challenges of big concurrency

1. Hard to find last tasks across all task pools
   - The worst case is for n == P
2. Speed of signal propagation via binary task tree
   - Classical equal splits spread the work slower
3. Thieves contention on victim's lock
   - Try_lock helps for $P > \log_2 n$
   - But still hard to start the first tasks..

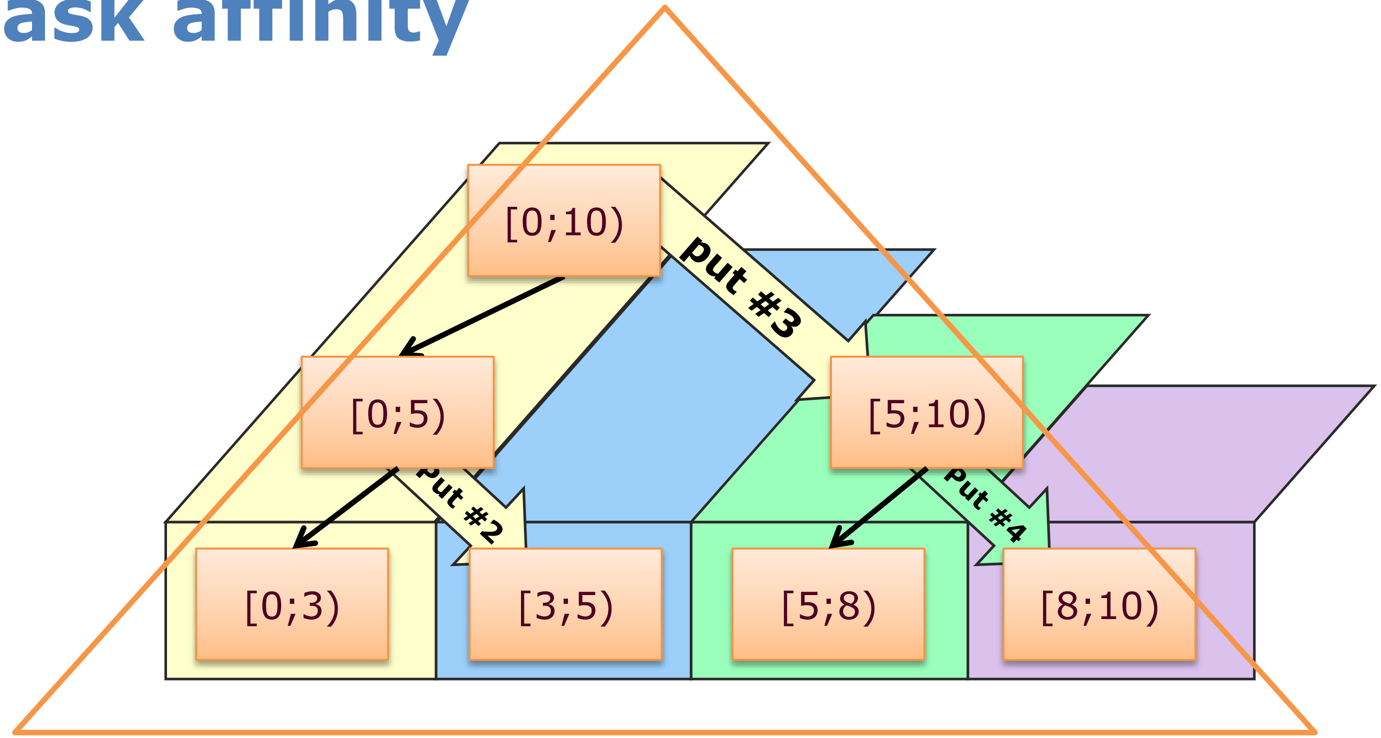


Work distribution through stealing: the conception (reminder)





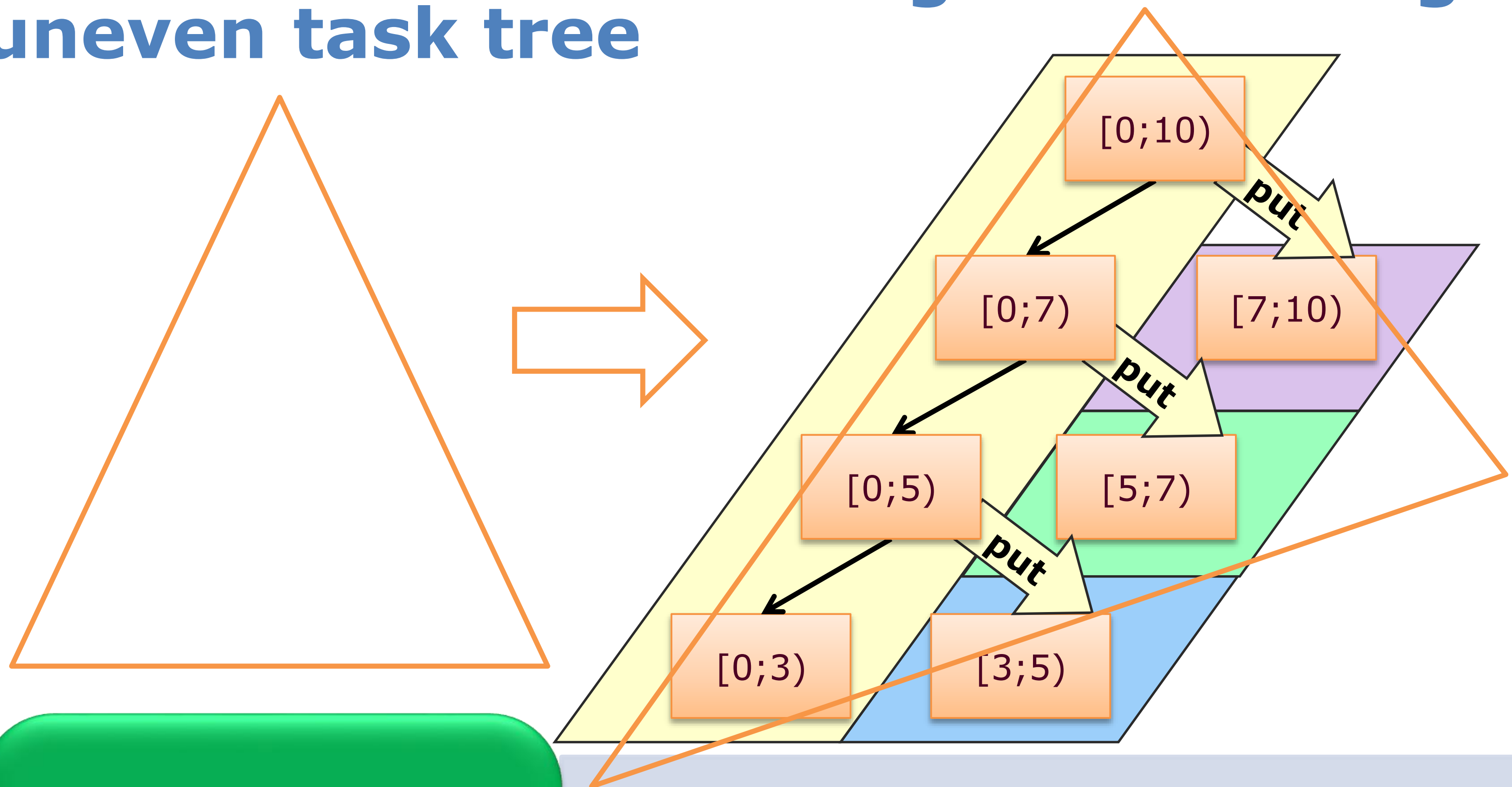
Work distribution through mailboxing: task affinity



Intel TBB task affinity

- Deterministic distribution via mailboxing
- No contention (SPSC communication)

Work distribution through mailboxing: uneven task tree



Unbalanced (lopsided) task tree

- Sending signal is faster than receiving it
- Earlier threads produce more tasks than later threads (not serialized!)
- Split in a proportion, not in half

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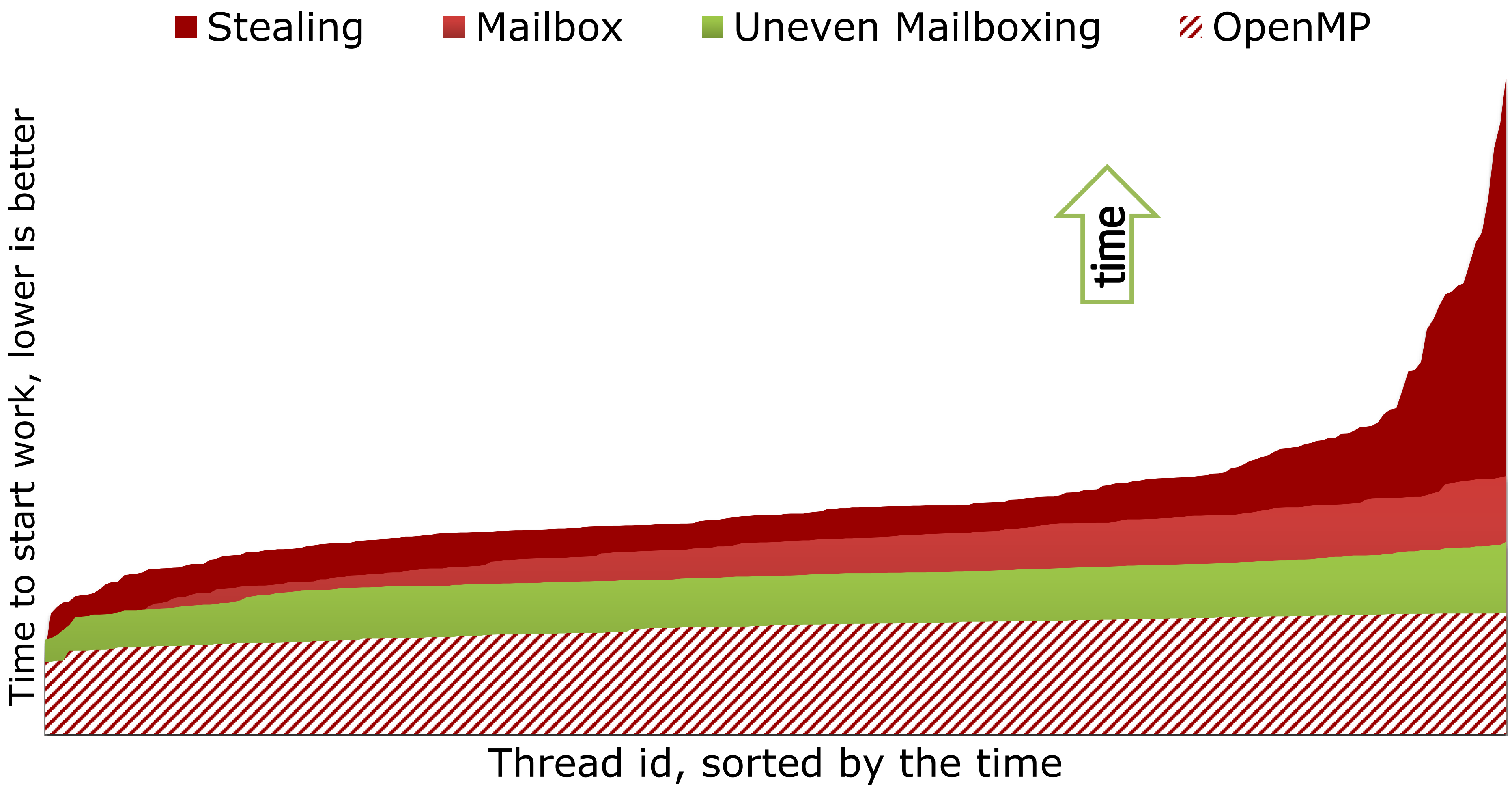
Start of 240 tasks, 1 per thread



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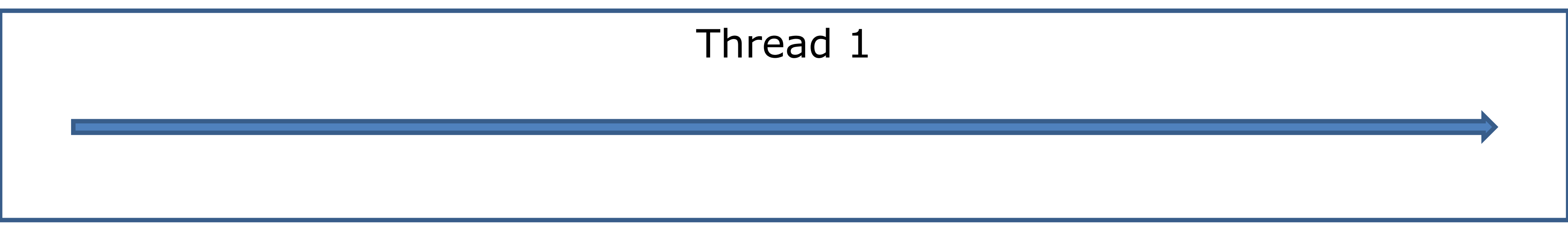
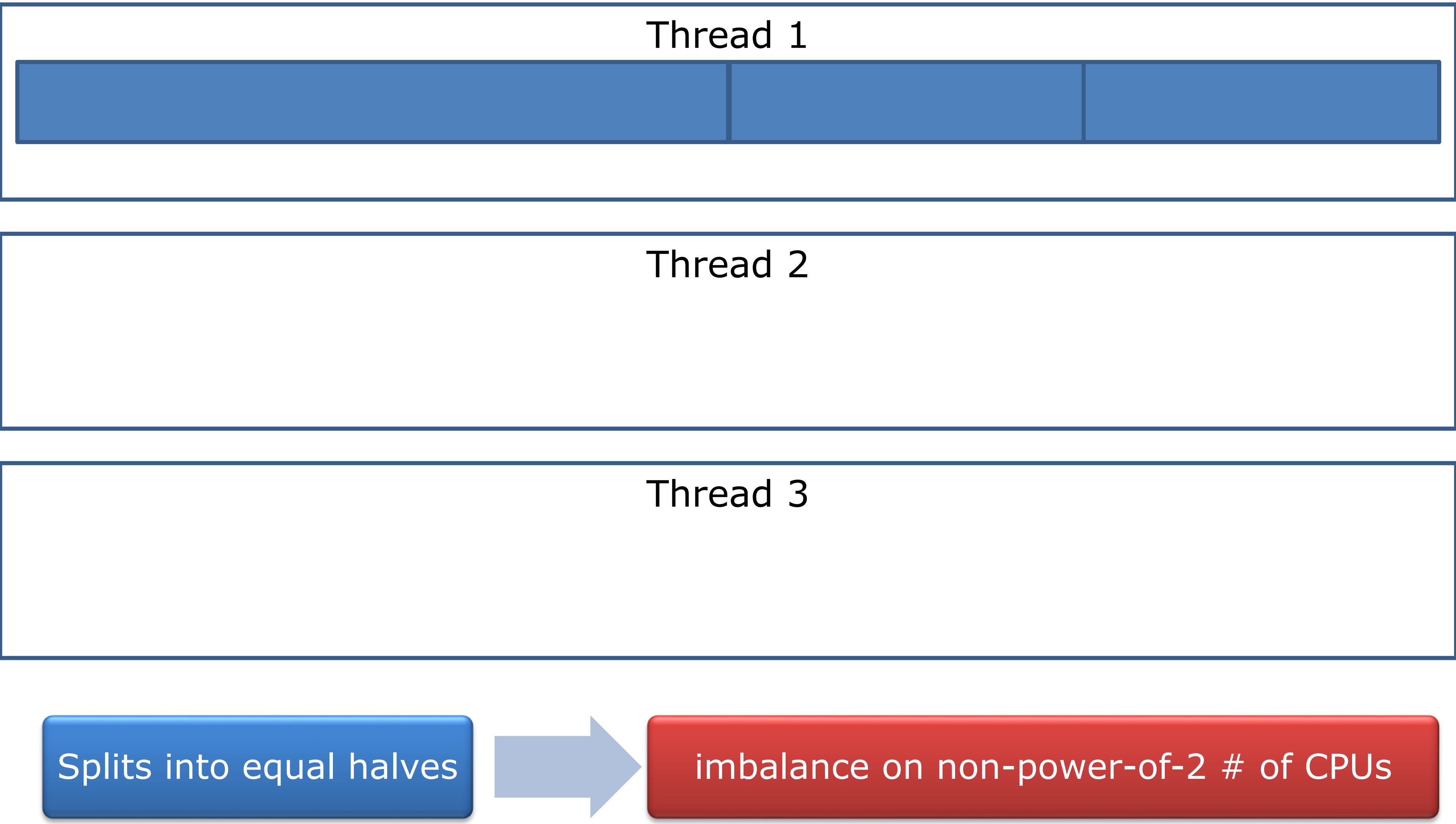
Distribution: work's point of view

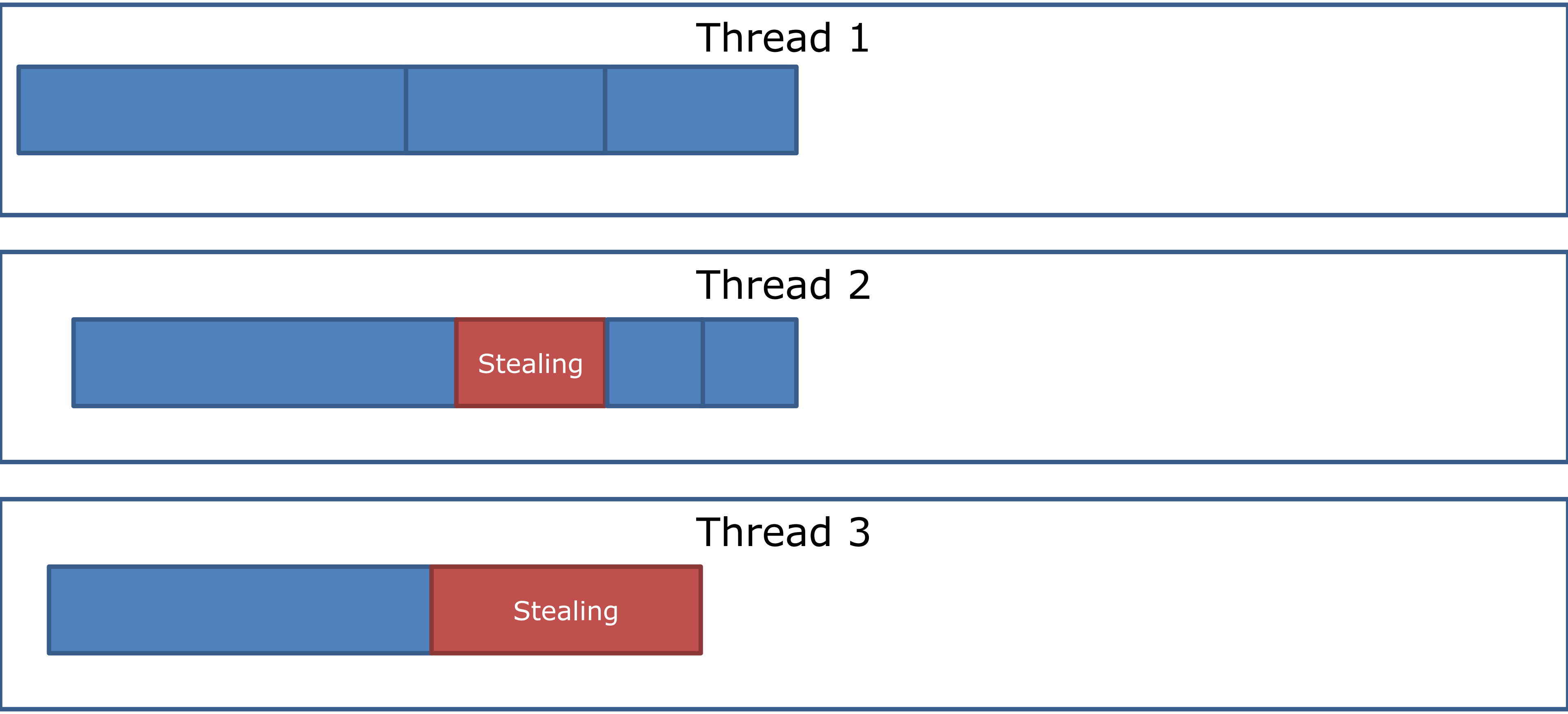
The thread, timeline



Simple work distribution: splitting

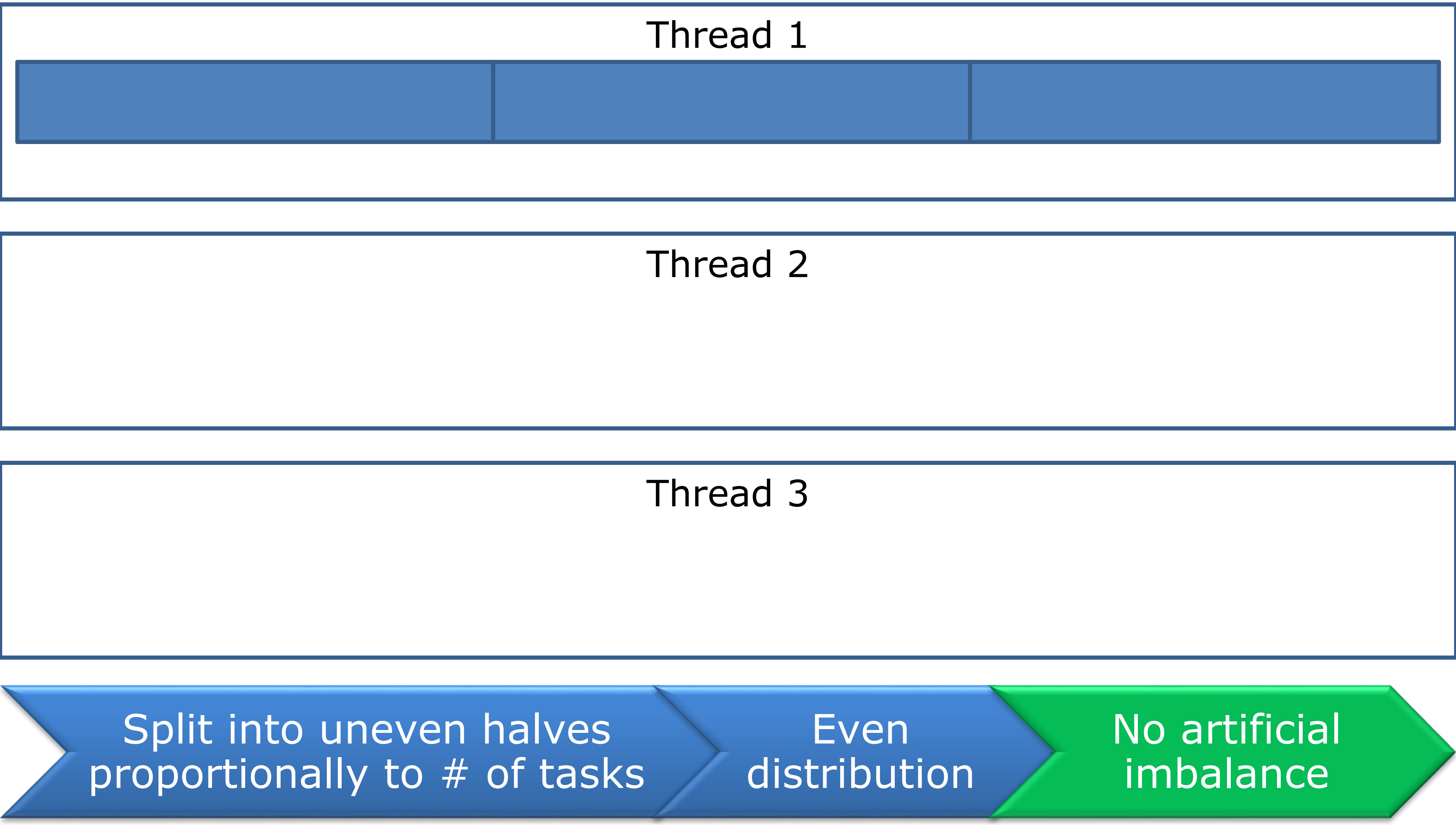


Simple work distribution: balancing

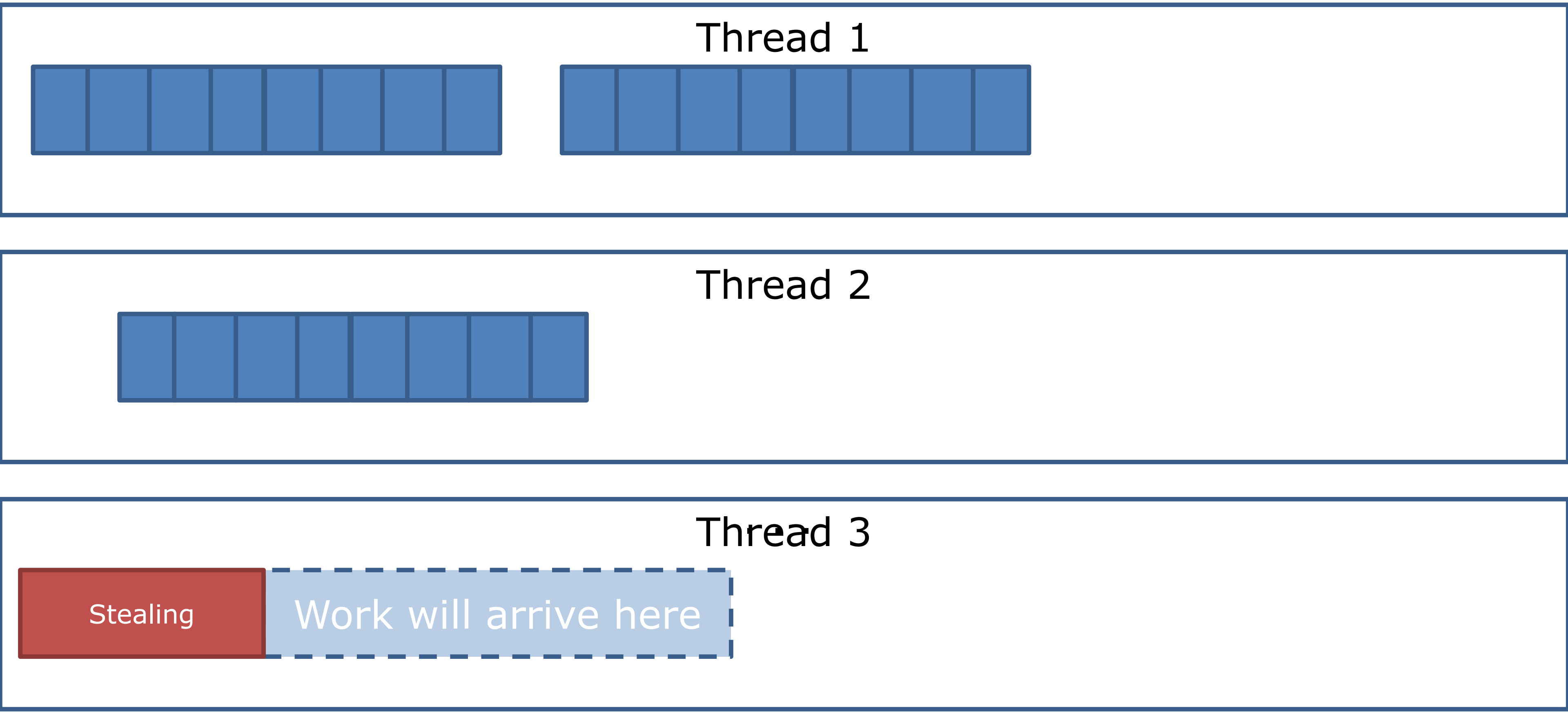


Can lead to inefficient stealing at the end, small grain-sizes

Proportional splitting

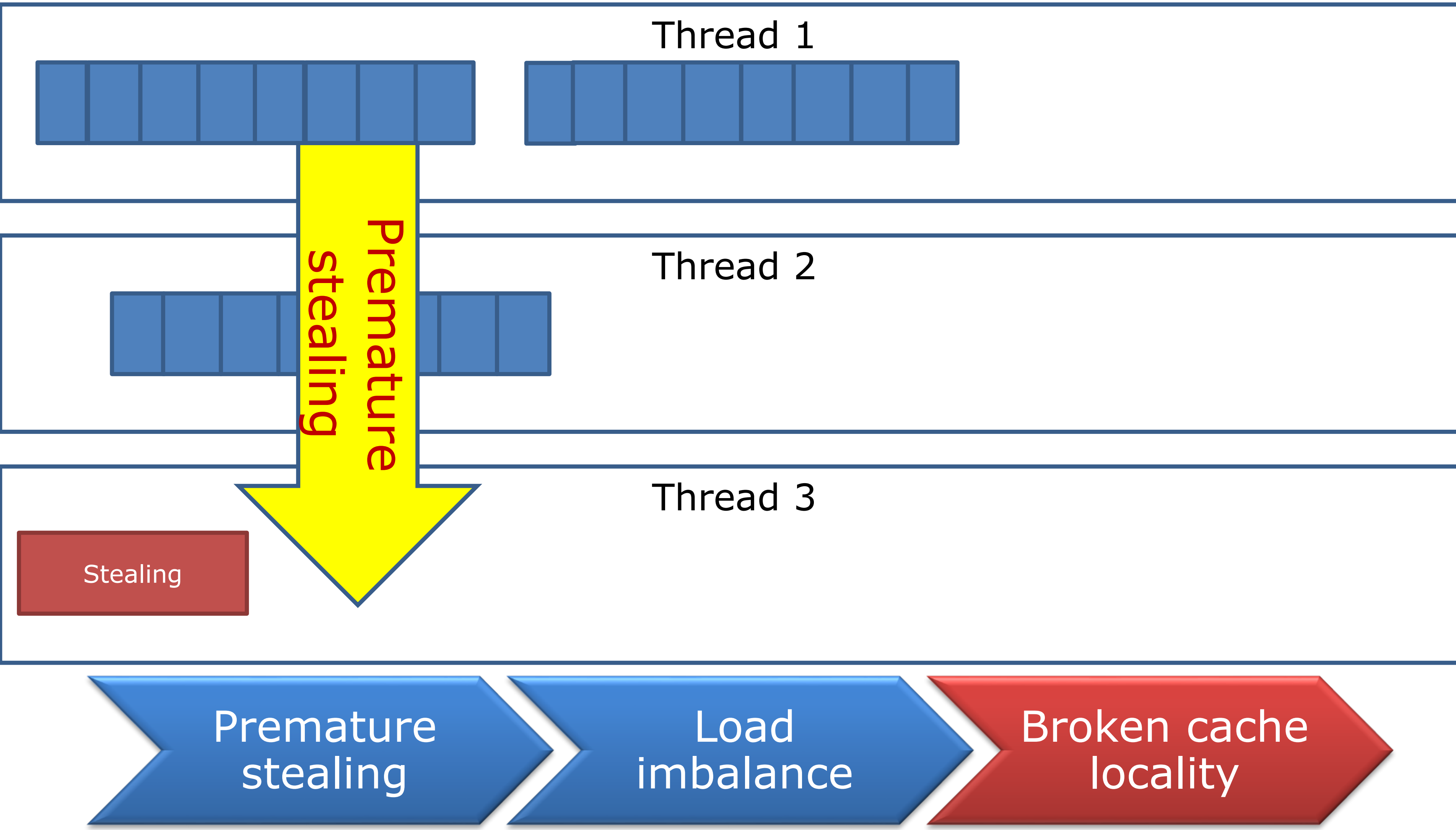


Premature stealing in Intel TBB



Stealing can occur earlier than the work supposed for the thread arrives

Premature stealing in Intel TBB



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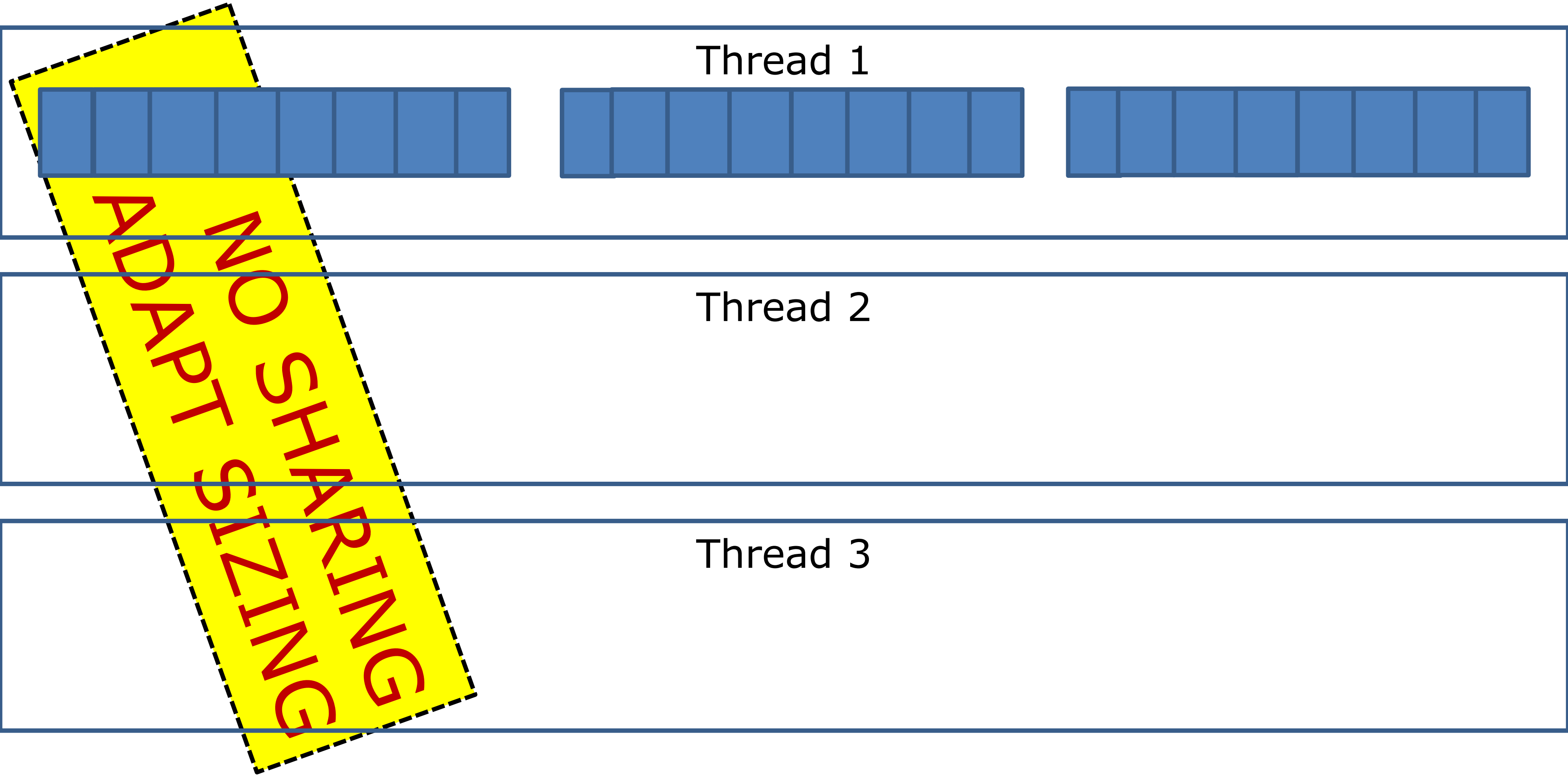
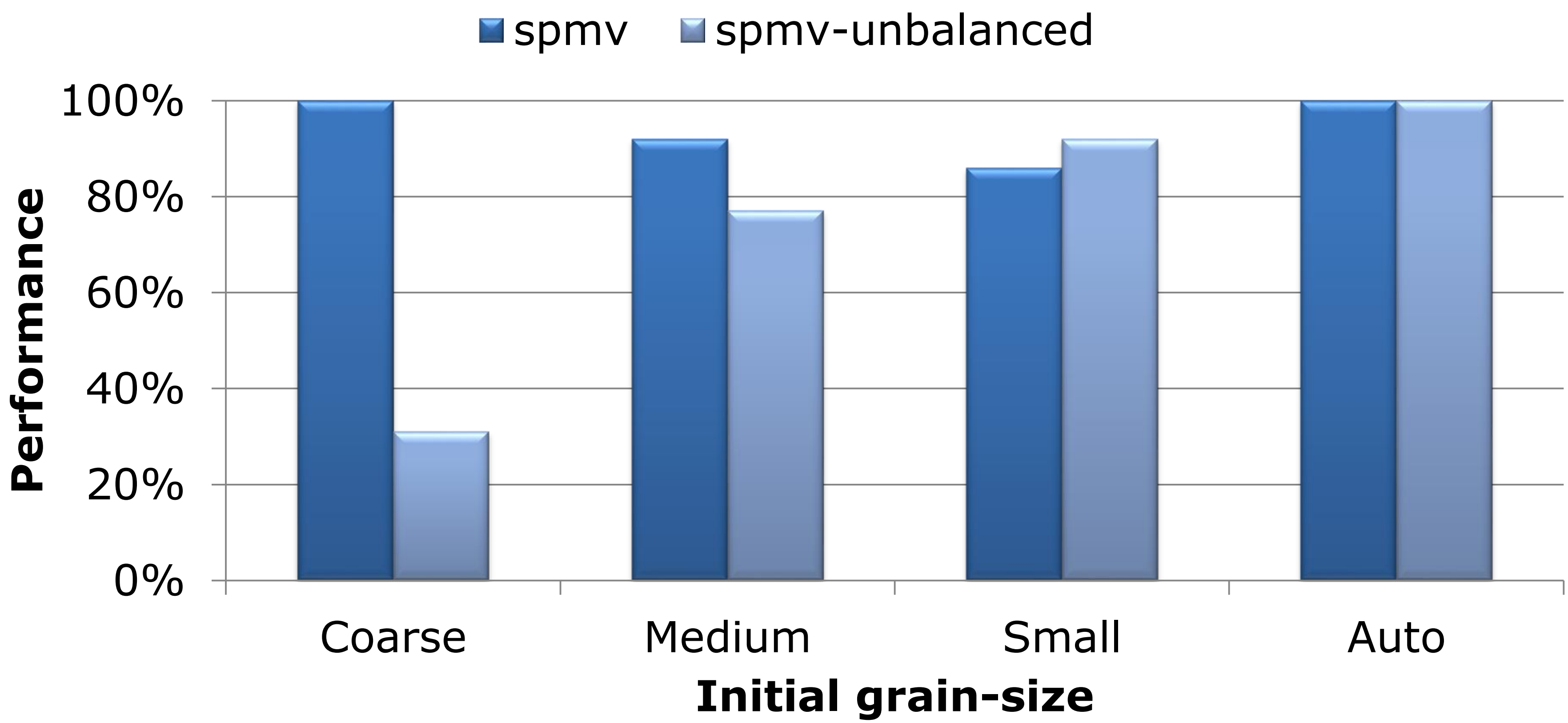
Solving last problems



RDTSC is used to put a ban on sharing the work → Also coarsen grain-size during this interval

Effect of automatic initial grain-size



Universal solution provides good performance for both balanced and unbalanced workloads

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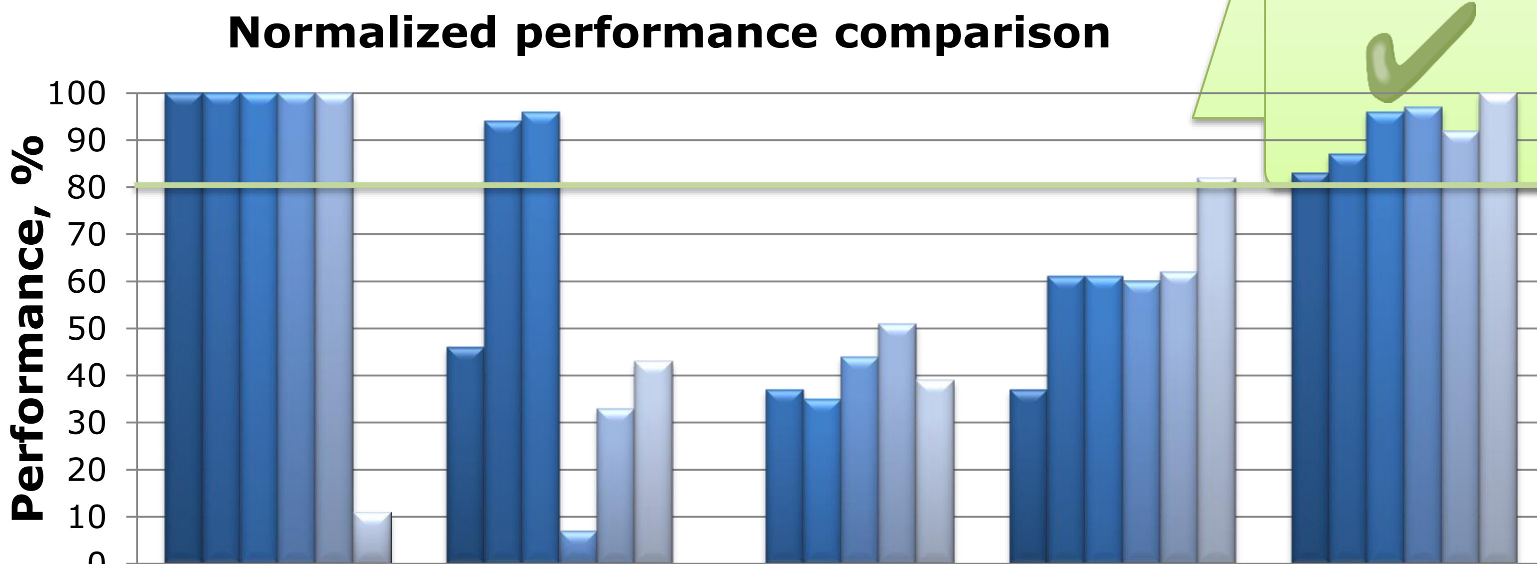
Final results



Threading: / Benchmarks	omp static	omp dynamic	TBB 4.1 defaults	TBB 4.2 U2 defaults	opencl partitioner
minimal	100	46	0	37	83
conformance	100	94	37	61	87
reduction	100	96	35	61	96
scan	100	7	44	60	97
spmv	100	33	51	62	92
spmv-unbalanced	11	43	39	82	100

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Summary

Started from up to 3x gap with OpenMP* static

Major solutions:

Using task affinity	Unbalanced task tree	Even work distribution	Adaptive delay	Dynamic grain-size

Almost closed gaps with OpenMP* static

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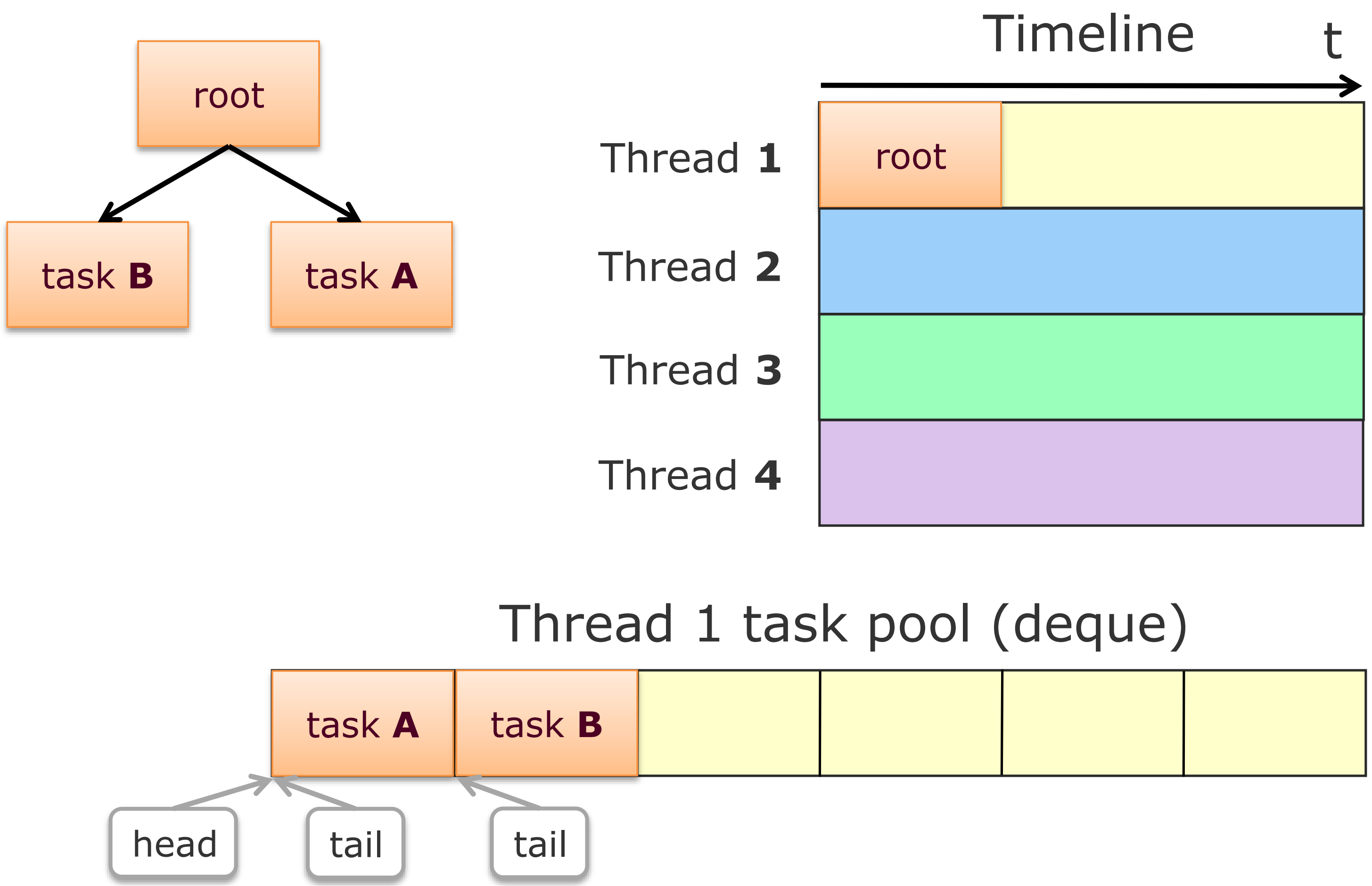
Notice revision #20110804

Executing and stealing tasks



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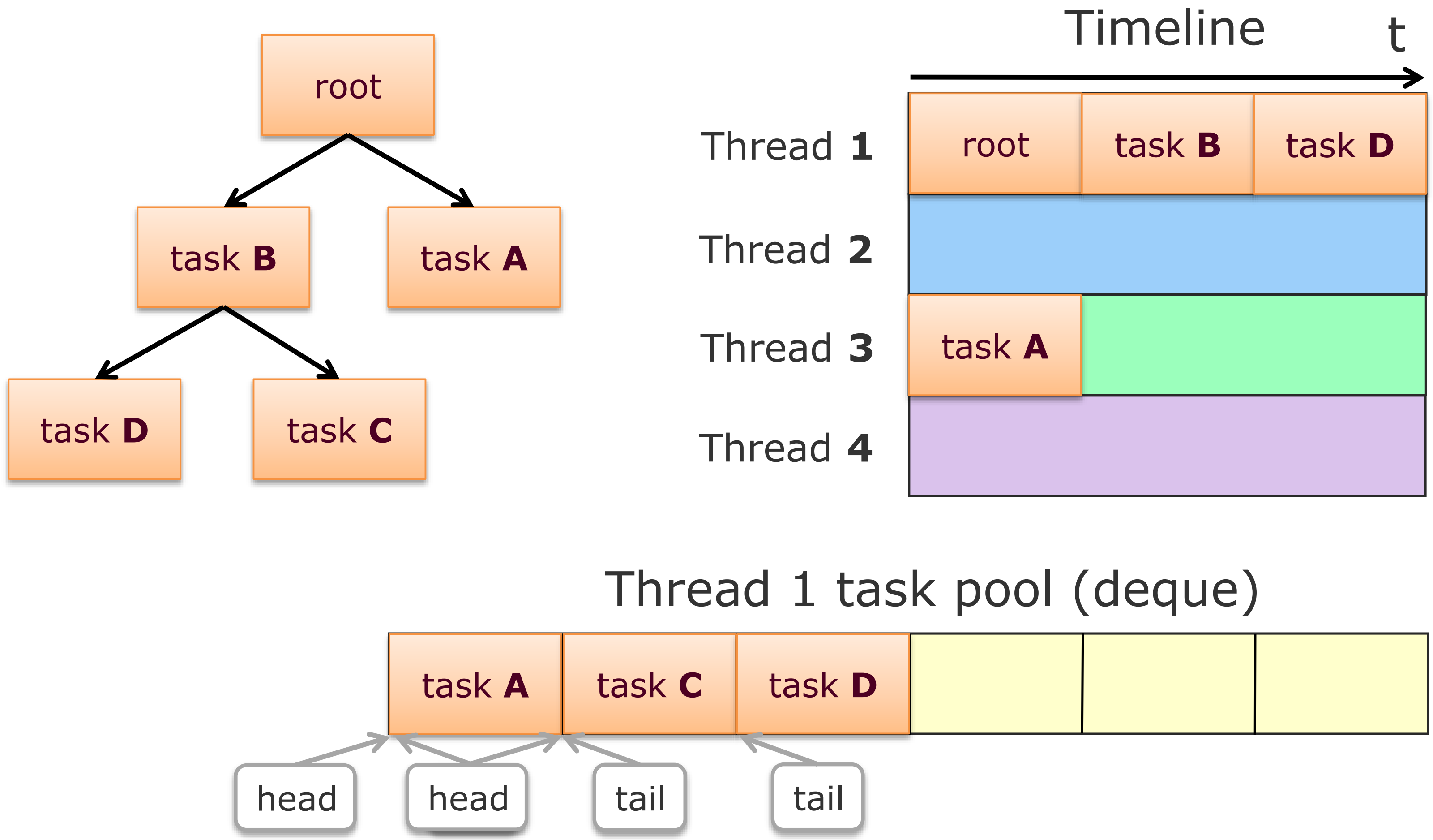
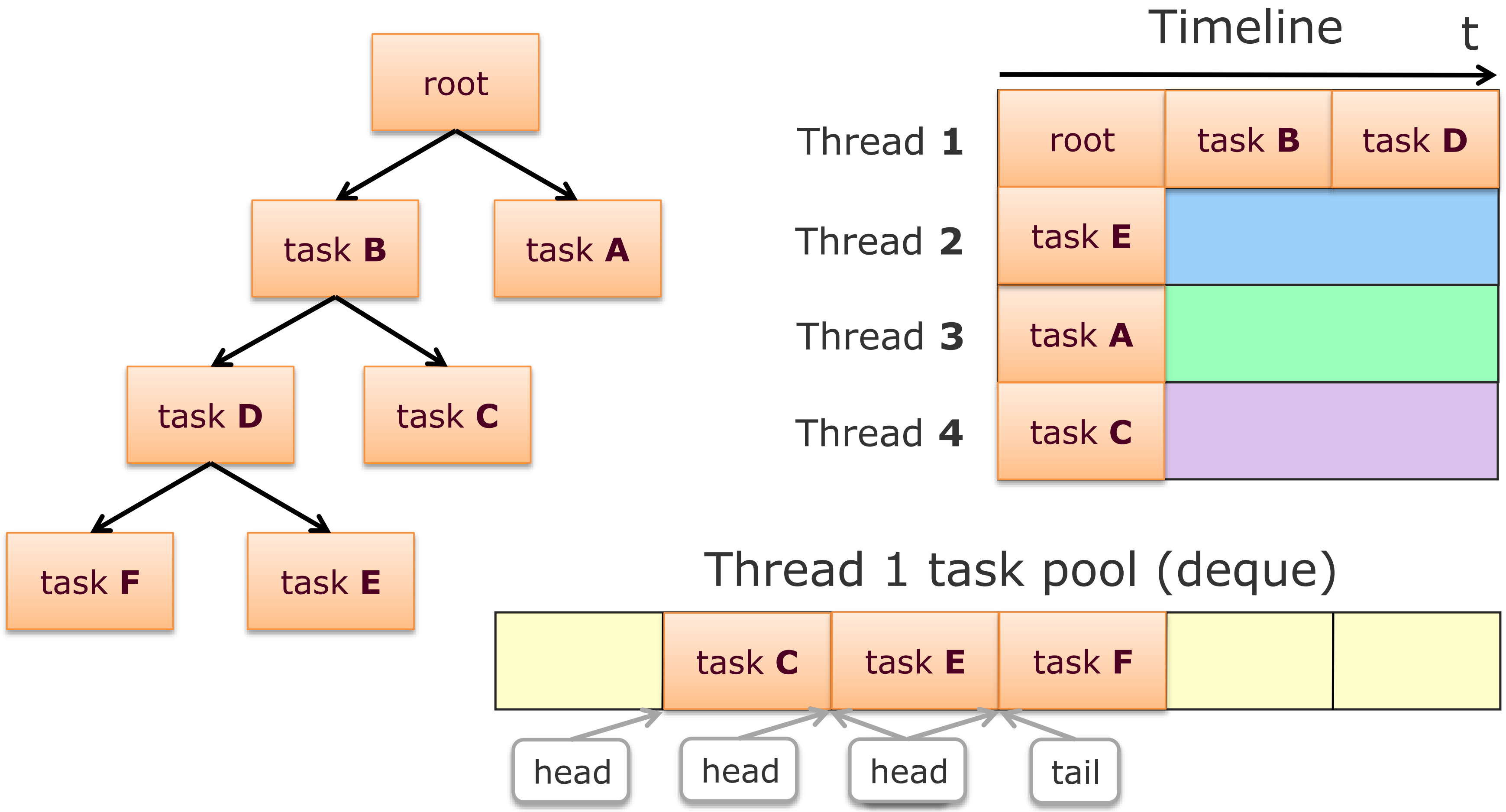
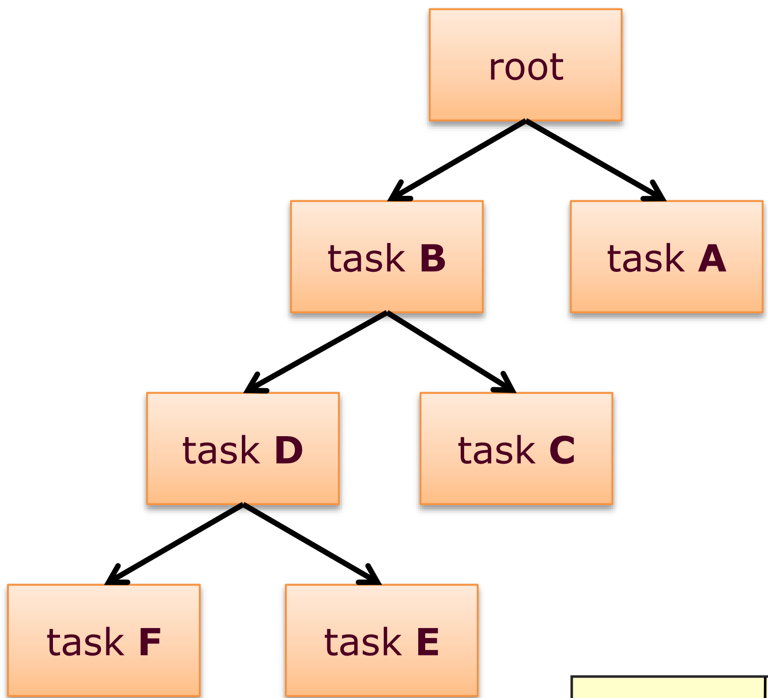
Executing and stealing tasks

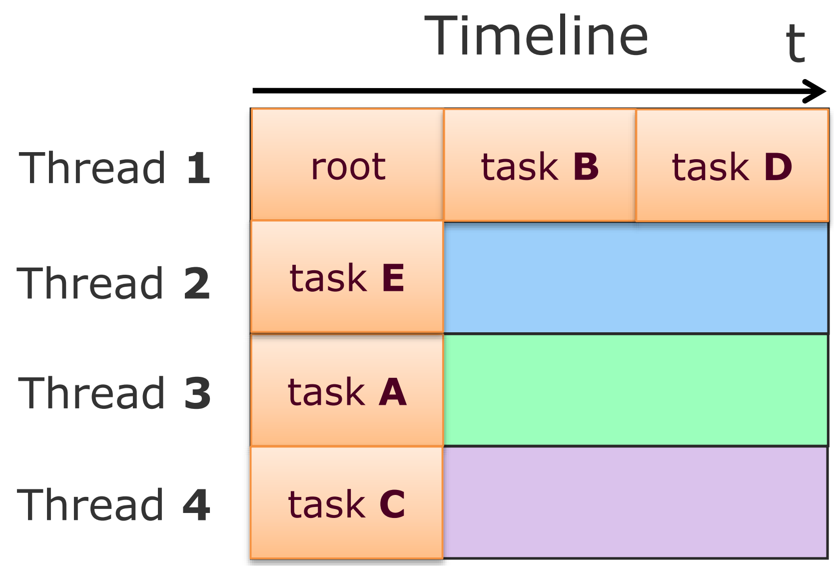


Executing and stealing tasks

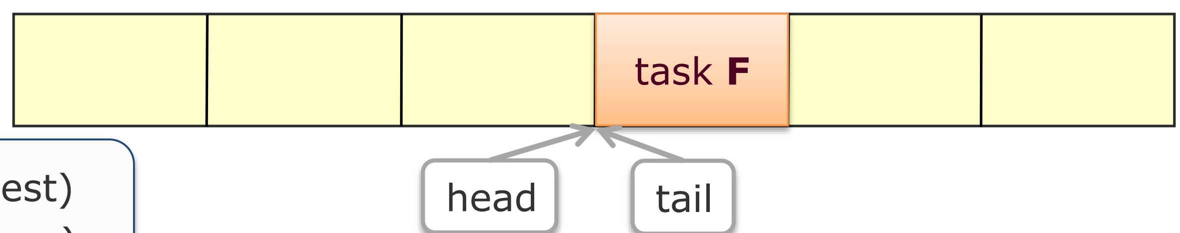


Executing and stealing tasks





Thread 1 task pool (deque)



executing from the back (newest)
stealing from the front (old/large)

when (tail – head) > 1, adding or taking tasks by local owner from a task pool is lock free

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Distribution of 240 tasks to its threads

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