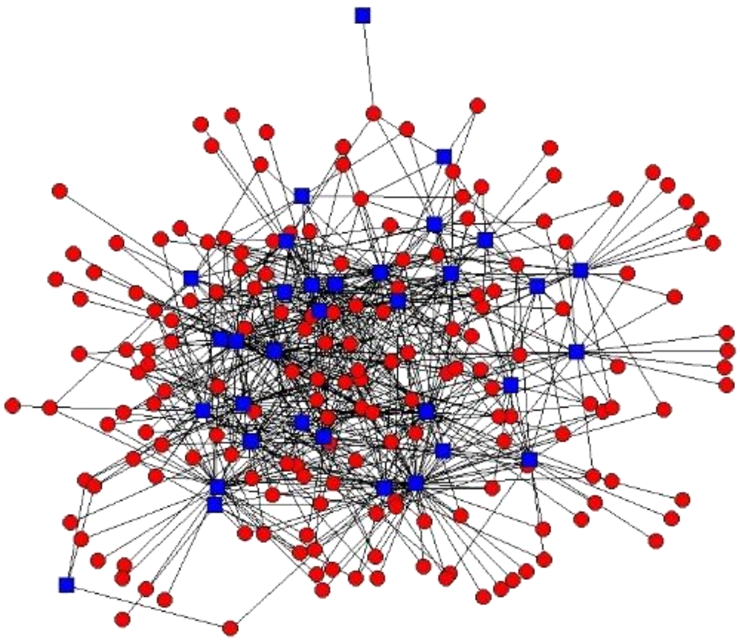
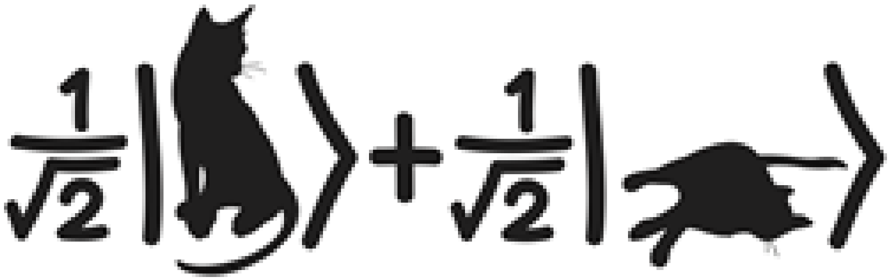
Accelerating Irregular Computations with Hardware Transactional Memory and Active Messages

MACIEJ BESTA, TORSTEN HOEFLER

LARGE-SCALE IRREGULAR GRAPH PROCESSING

- Becoming more important [1]
  - Machine learning
  - Computational science
  - Social network analysis





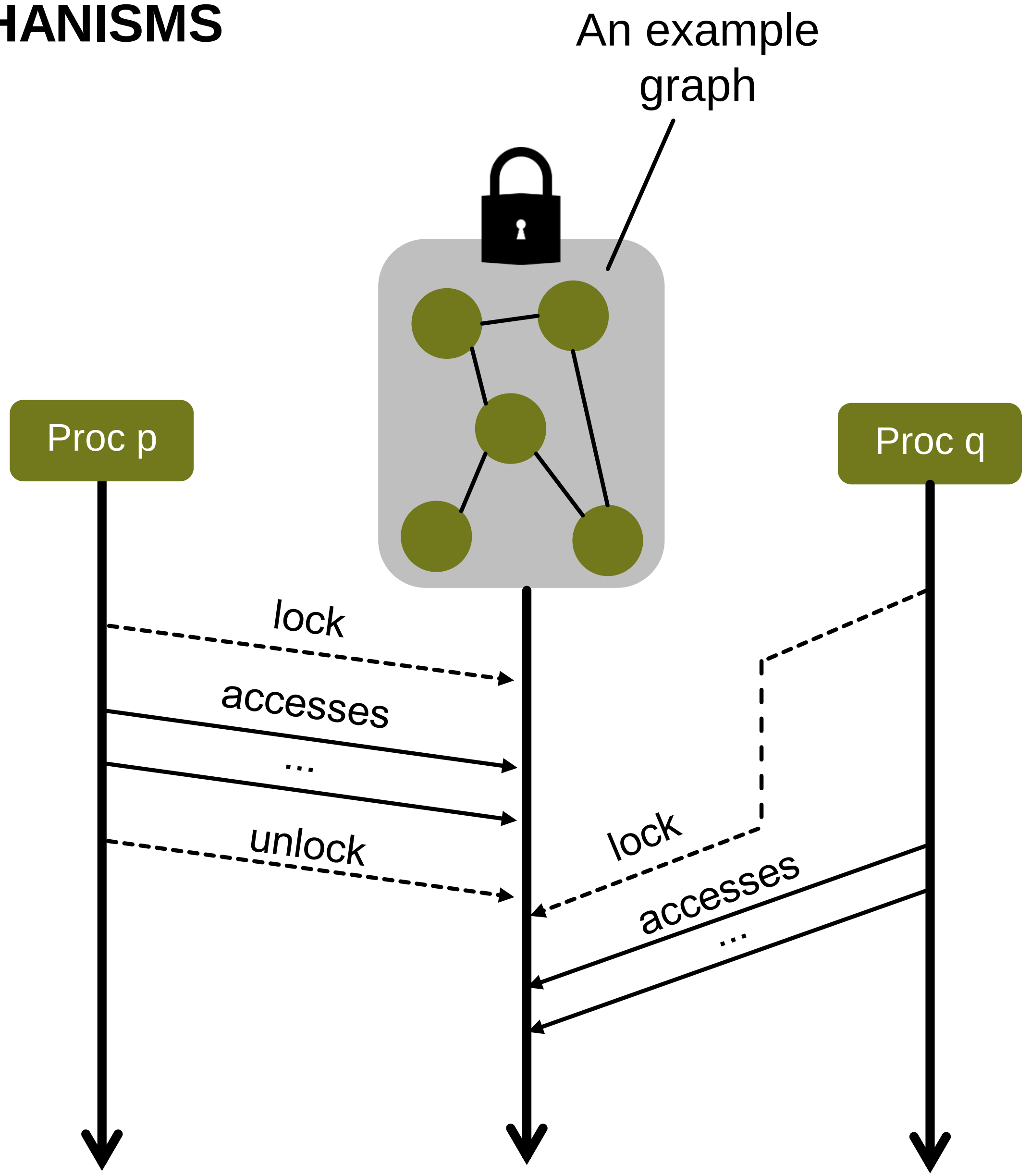
[1] A. Lumsdaine et al. Challenges in Parallel Graph Processing. Parallel Processing Let. 2007.

Synchronization Mechanisms
Coarse locks

Simple protocols

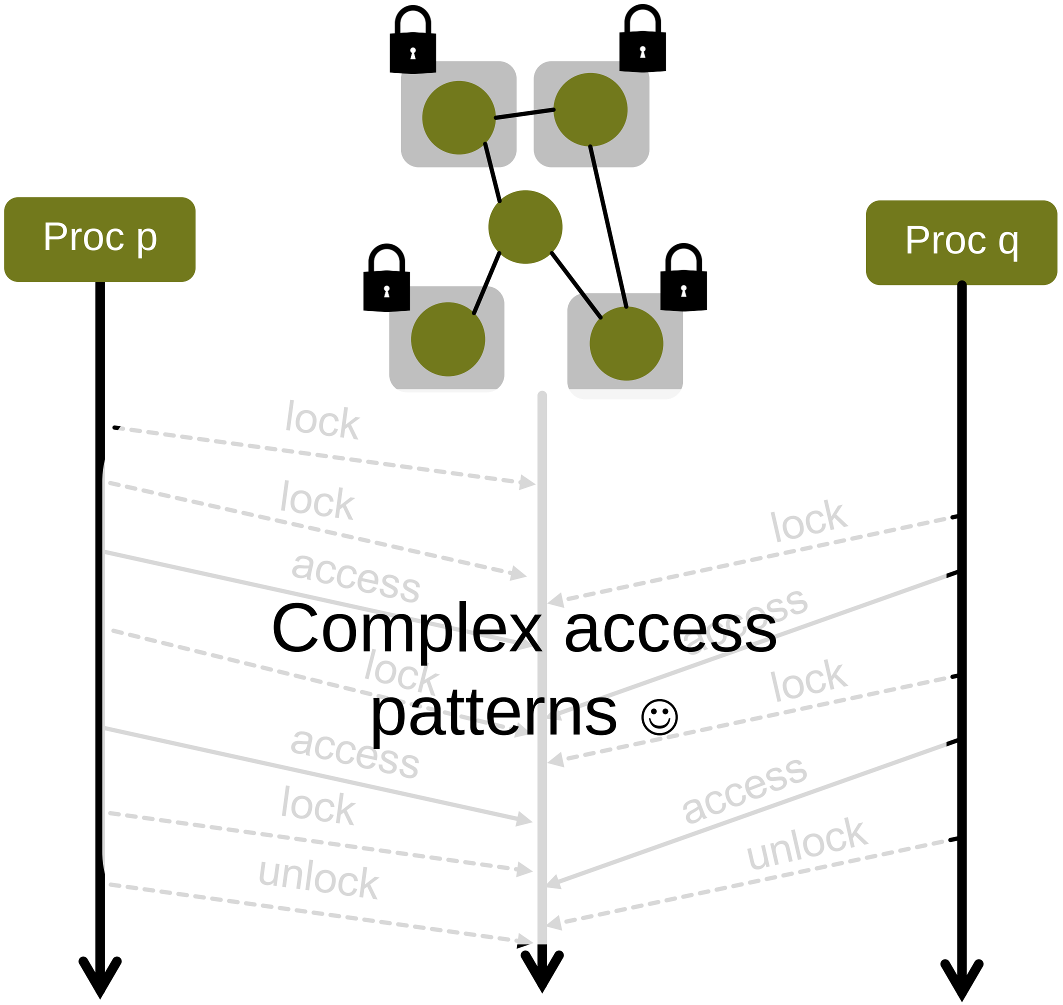
Serialization

Detrimental performance



Synchronization Mechanisms
Fine locks

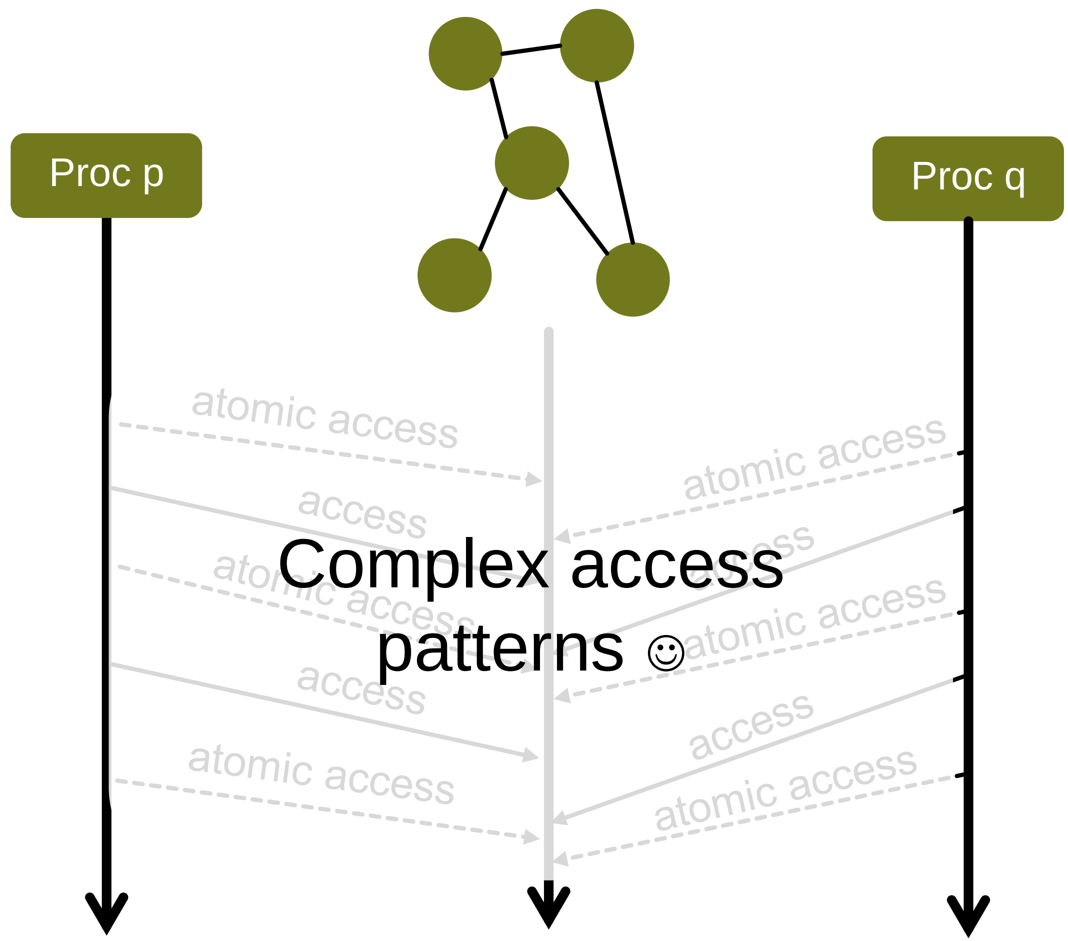
- Higher performance possible
- Complex protocols
- Risk of deadlocks



SYNCHRONIZATION MECHANISMS

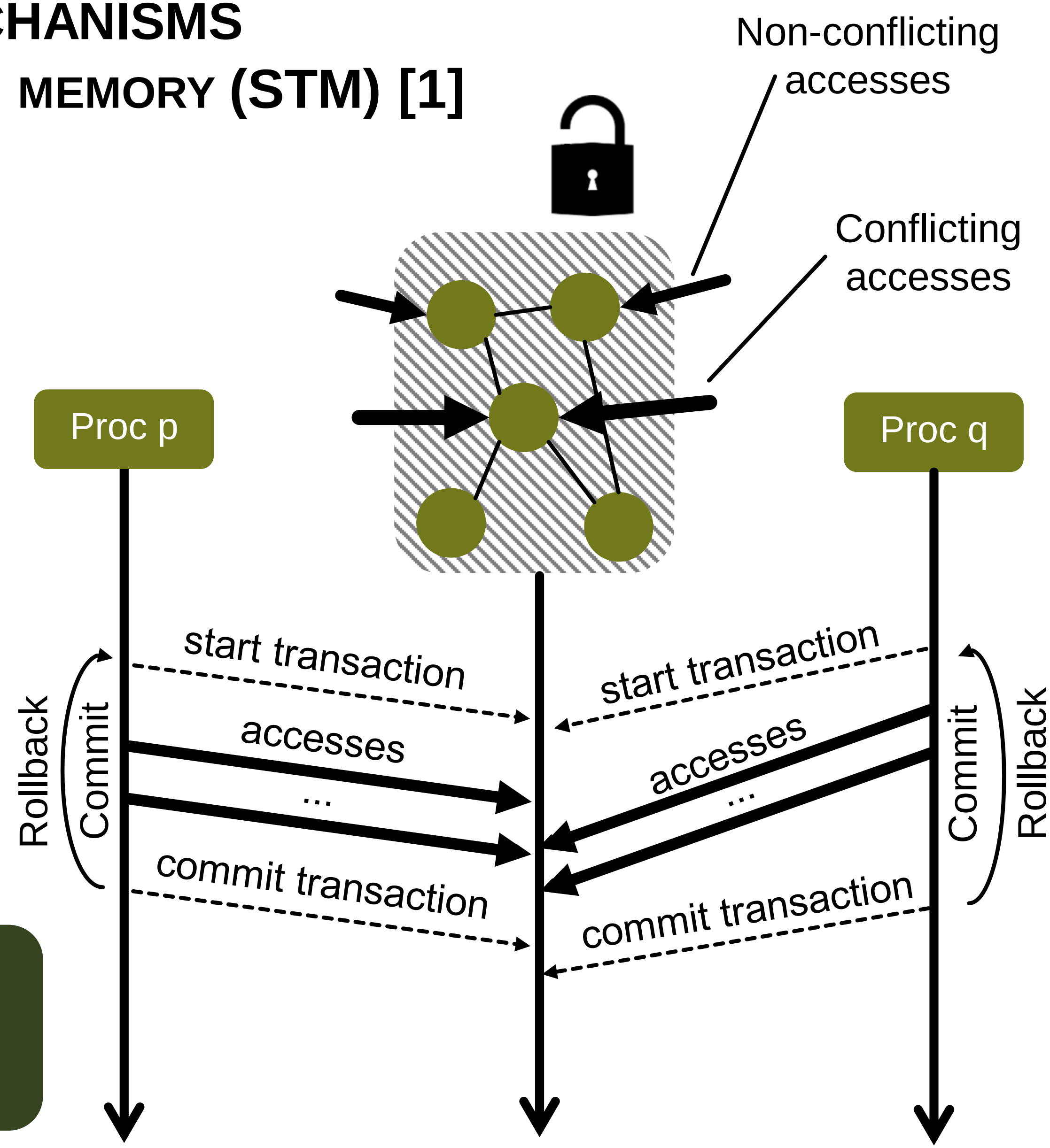
ATOMIC OPERATIONS

- ✔ High performance (may be challenging to get)
- ✘ Complex protocols
- ✘ Subtle issues (ABA, ...)



Synchronization Mechanisms
Software transactional memory (STM) [1]

Conflicts solved with rollbacks and/or serialization.



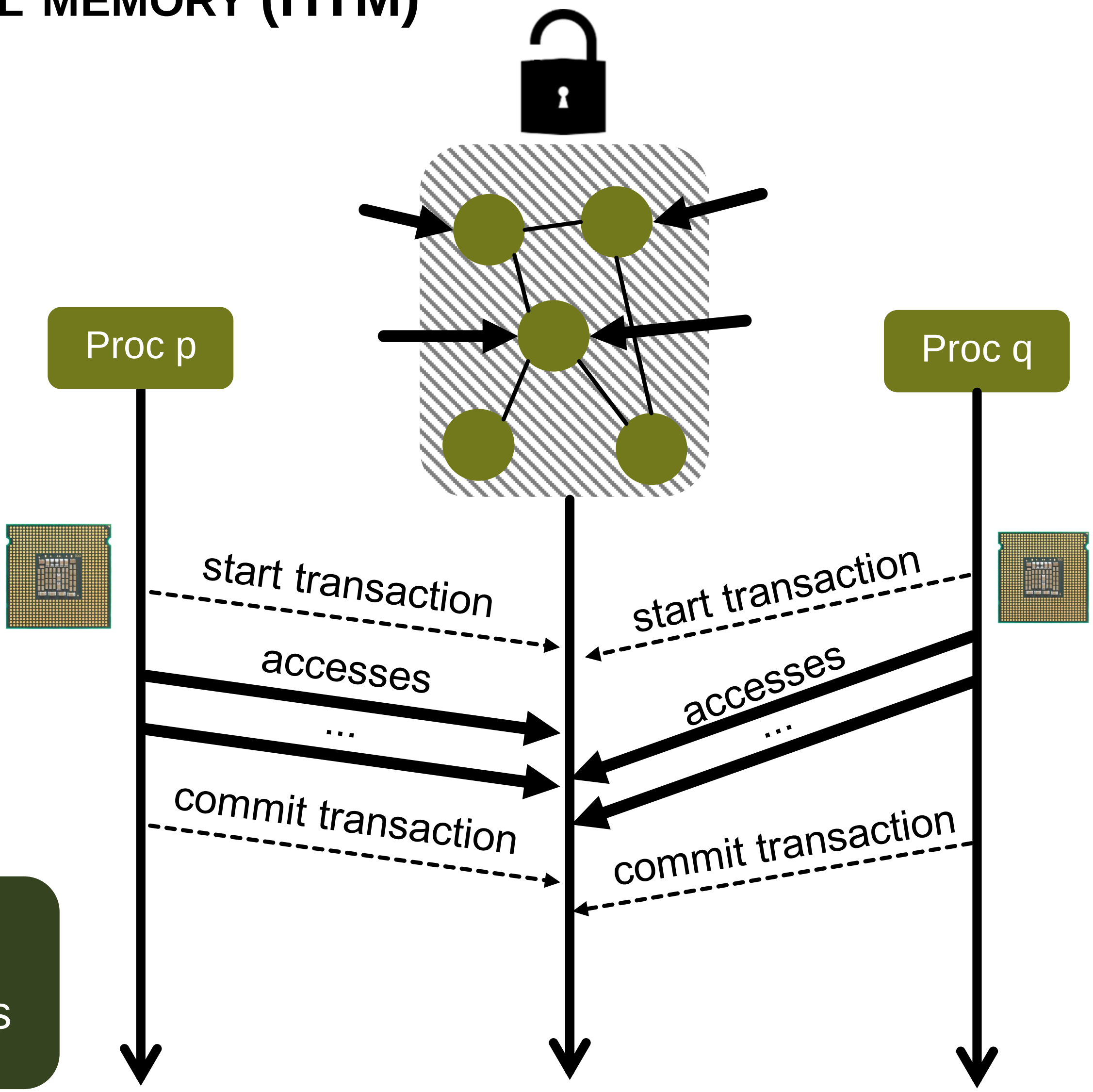
Software overheads

Simple protocols

[1] N. Shavit and D. Touitou. Software transactional memory. PODC'95.

Synchronization Mechanisms
Hardware transactional memory (HTM)

Conflicts solved with rollbacks and/or HW serialization.



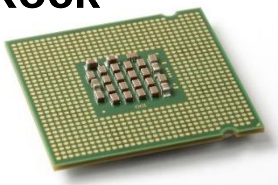
High performance? For graphs?

Simple protocols

Hardware Transactional Memory

Vega

Rock



BlueGene/Q

POWER8

Haswell

Hardware Transactional Memory

Sun microsystems

Rock

AZUL SYSTEMS

Vega

IBM

BlueGene/Q

They offer programmability, how about performance?

Haswell

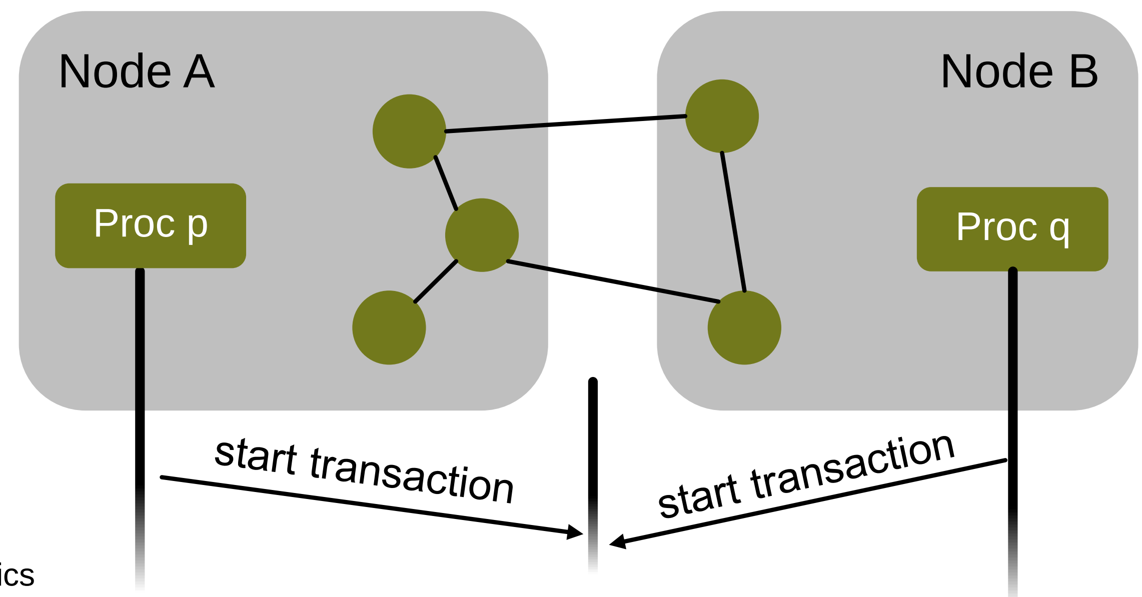
intel

POWER8

Shared- & Distributed-memory Machines

- HTM works fine for single shared-memory domains
  - Most graphs fit in such machines [1]
- However, some do not:
  - Very large instances
  - Rich vertex/edge data
- Fat nodes with lots of RAM still expensive ($35K for a machine with 1TB of RAM [1])

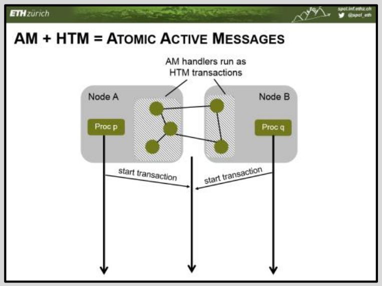
How to apply HTM in such a setting?



[1] Y. Perez et al. Ringo: Interactive Graph Analytics on Big-Memory Machines. SIGCOMM'14.

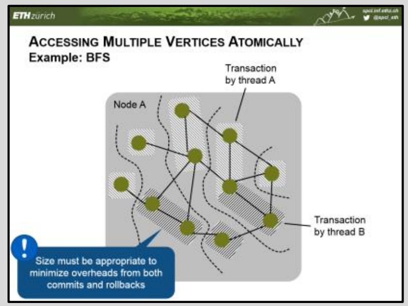
Overview of our Research

AAM Design

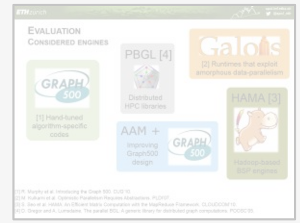


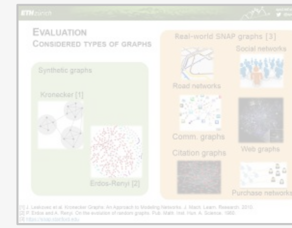
Active Messages + HTM

Coarsening & coalescing

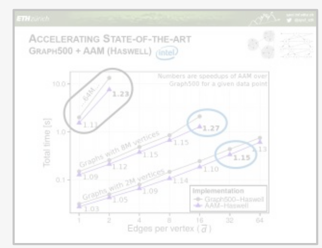


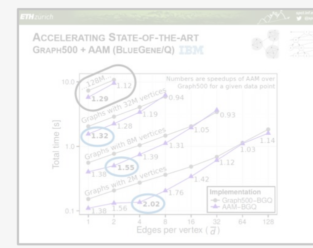
Evaluation



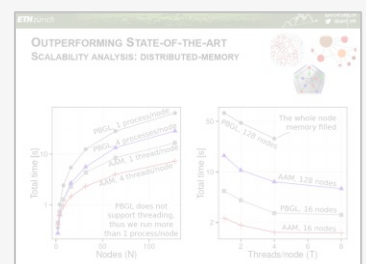


Considered engines and graphs





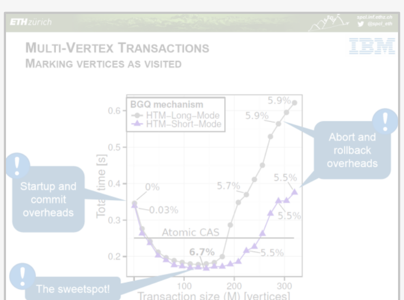
Accelerating state-of-the-art

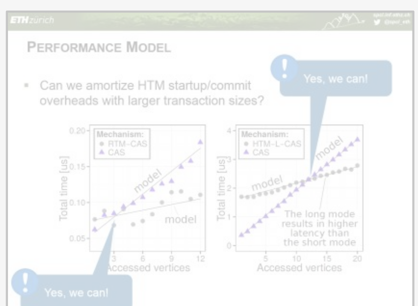


Scalability

Performance Modeling & Analysis

Haswell & BG/Q Analysis

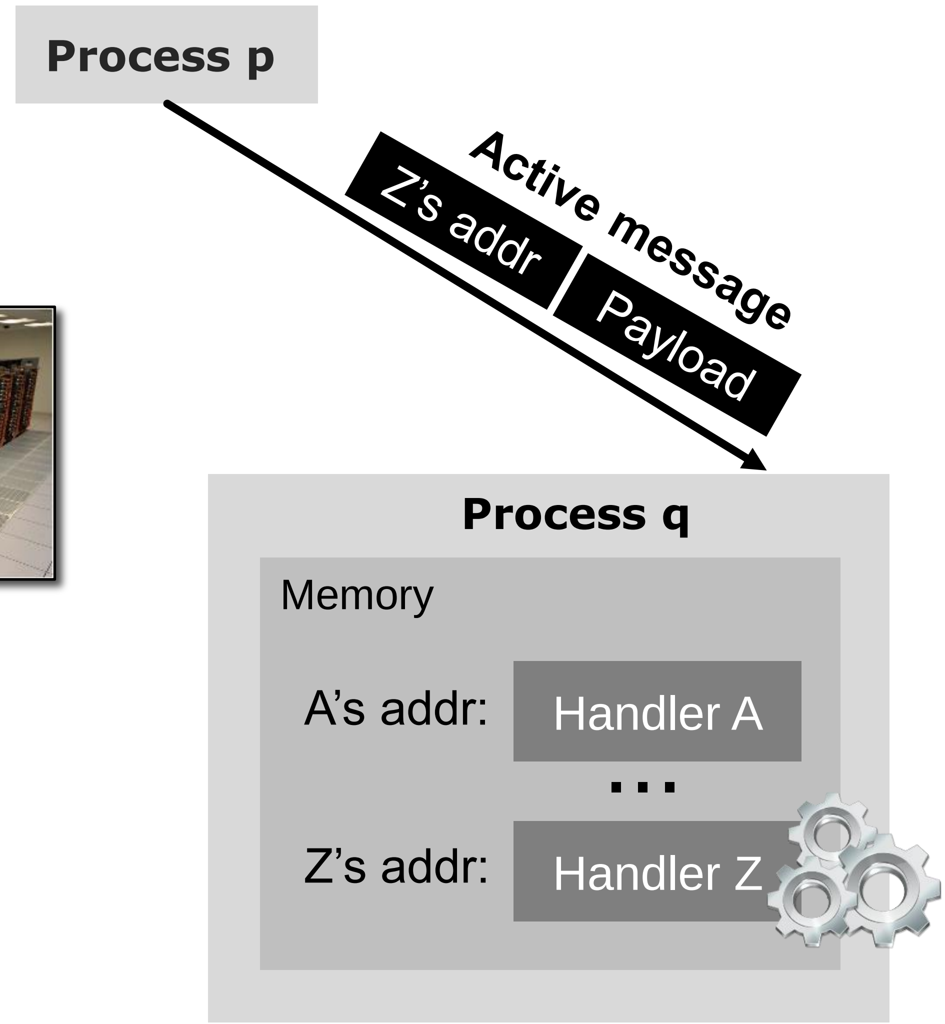




Performance model

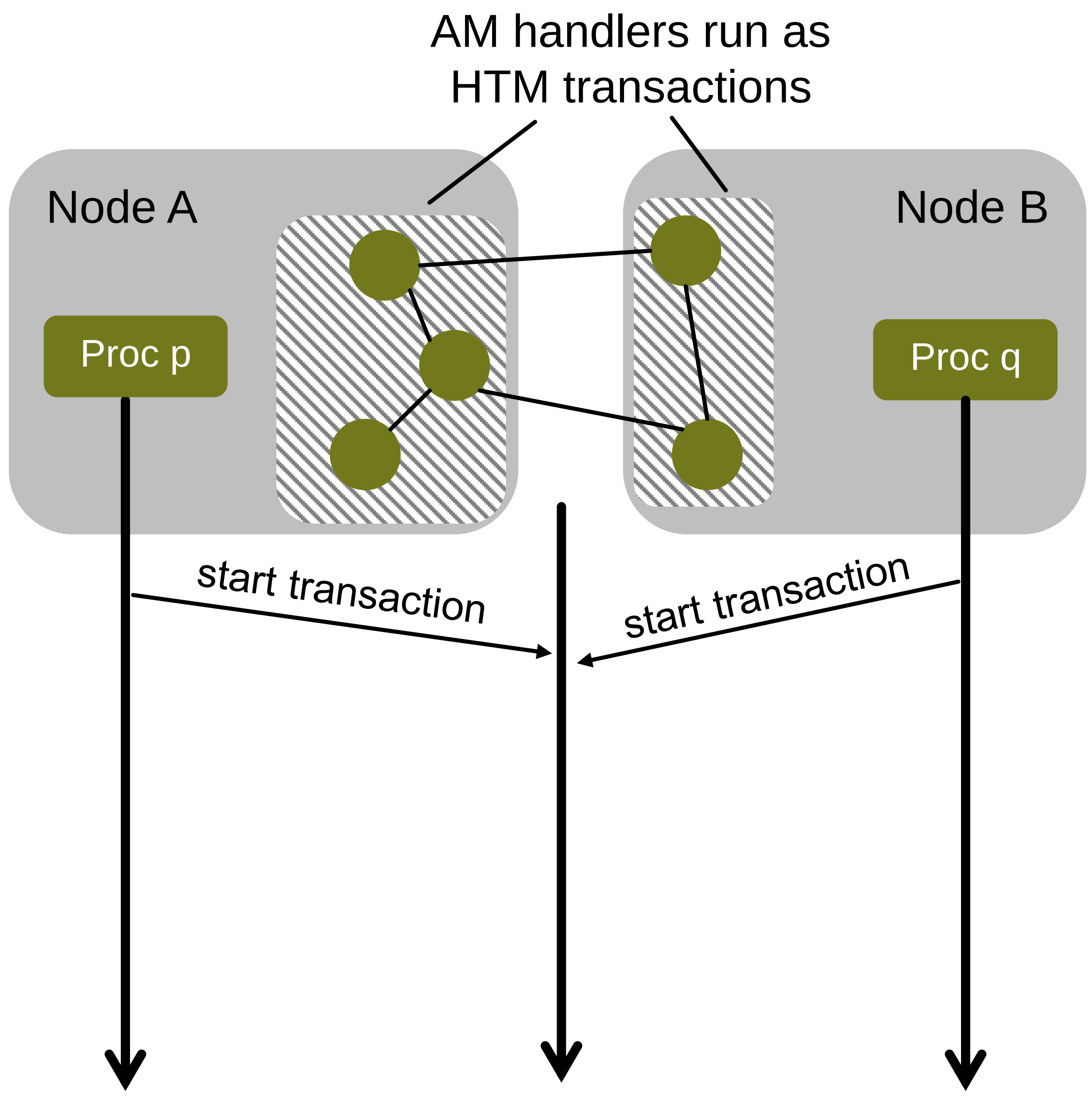
Active Messages (AM)

AM++[1] GASNet [2]



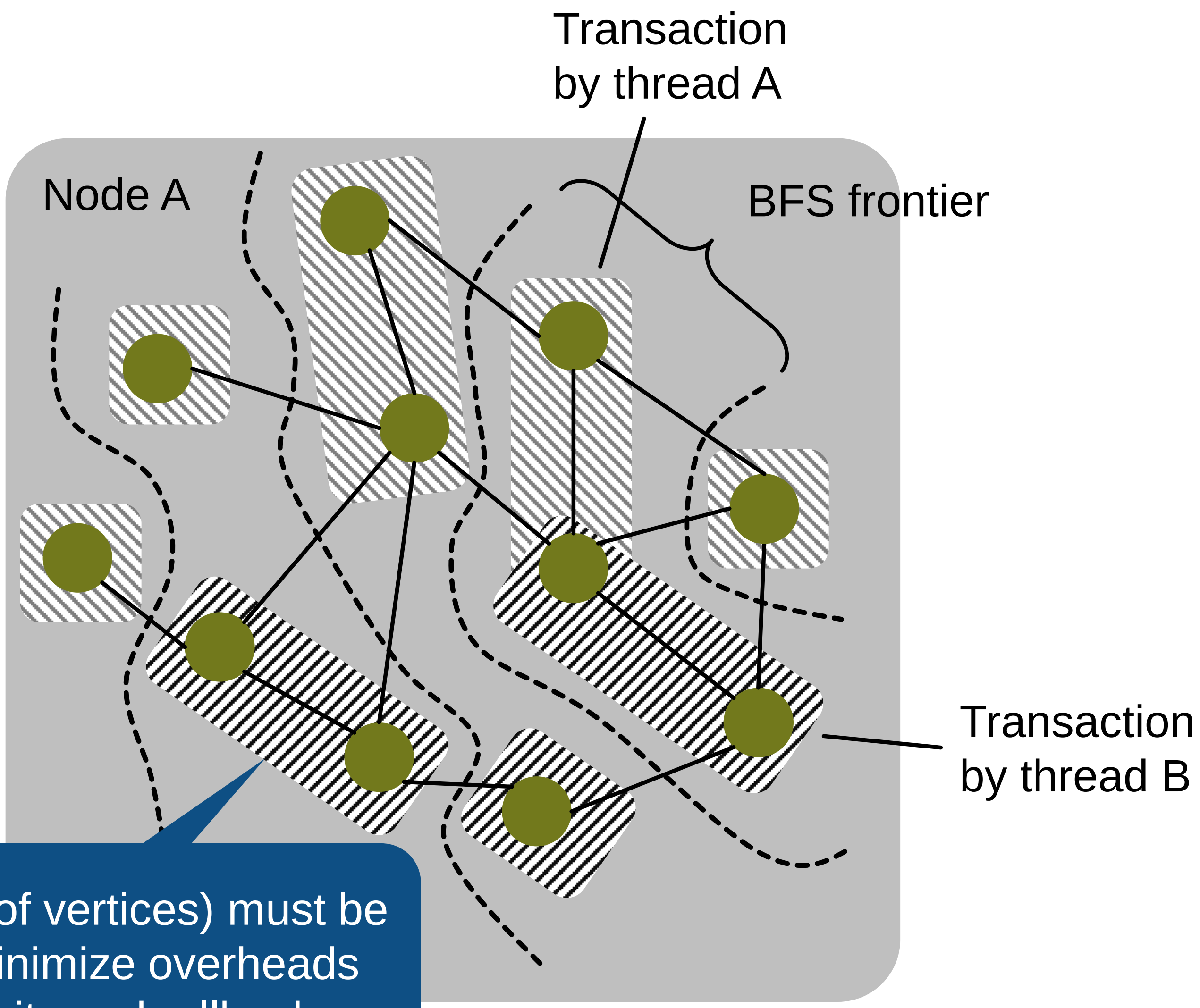
[1] J. J. Willcock et al. AM++: A generalized active message framework. PACT'10.
[2] D. Bonachea, GASNet Specification, v1.1. Berkeley Technical Report. 2002.

AM + HTM = Atomic Active Messages



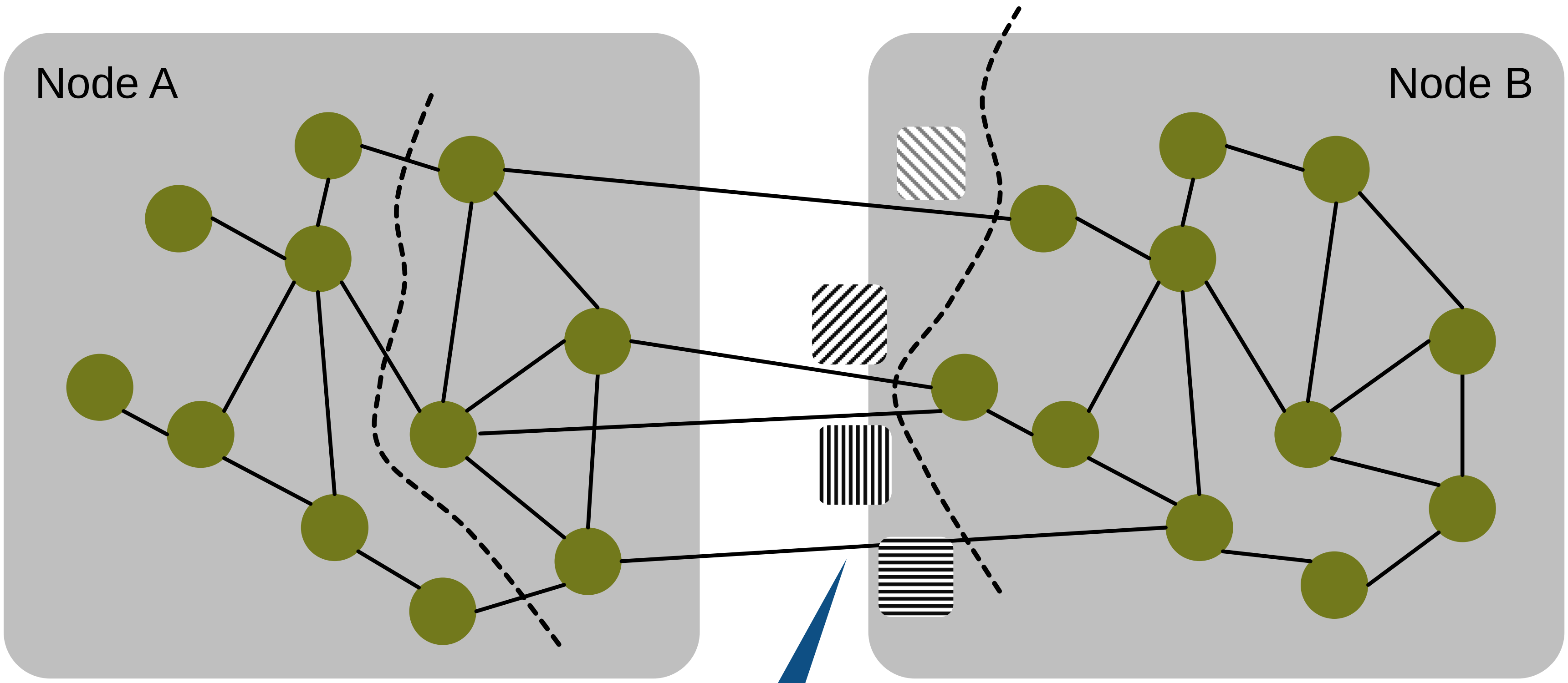
Accessing Multiple Vertices Atomically

Example: BFS



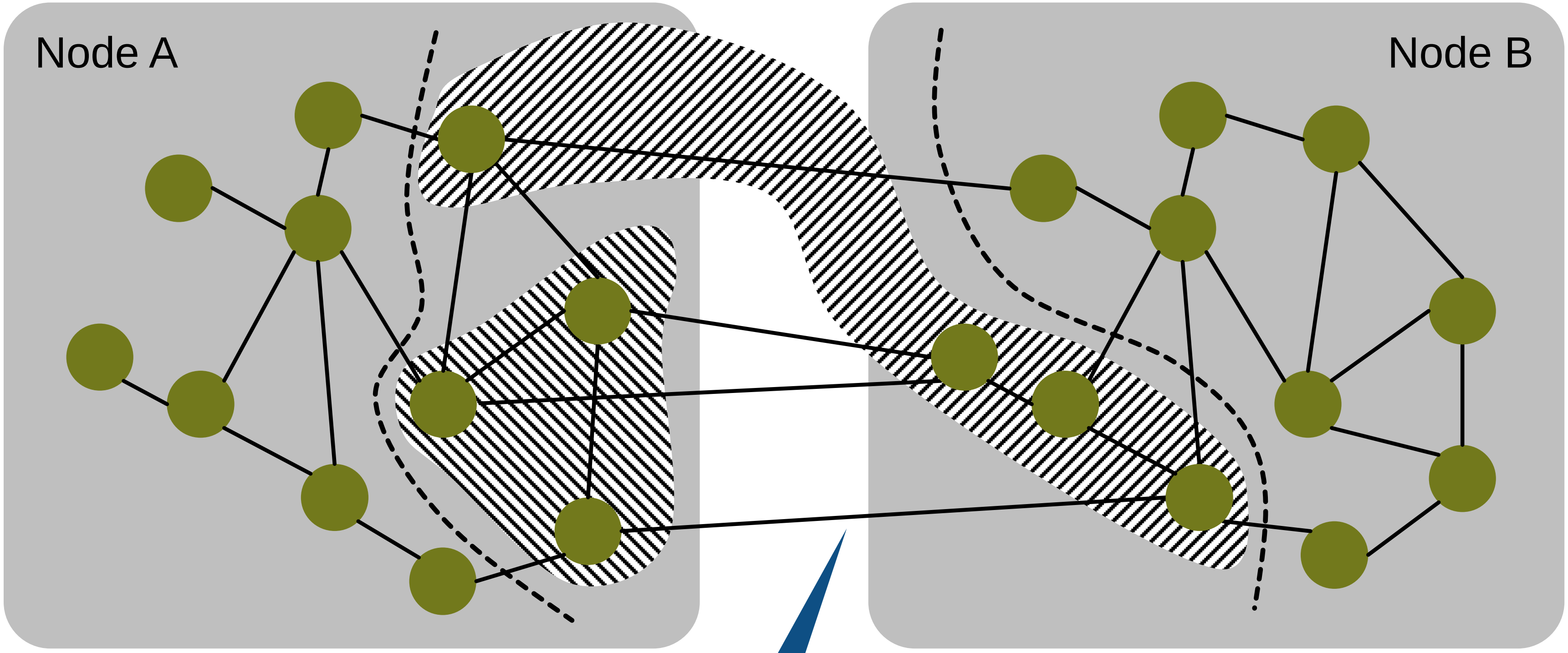
Size (the number of vertices) must be appropriate to minimize overheads from both commits and rollbacks

Transferring Transactions Across Nodes



Transactions must be appropriately coalesced to minimize communication overheads

Executing Transactions on Multiple Nodes



Vertices must be appropriately relocated to enable execution of a hardware transaction

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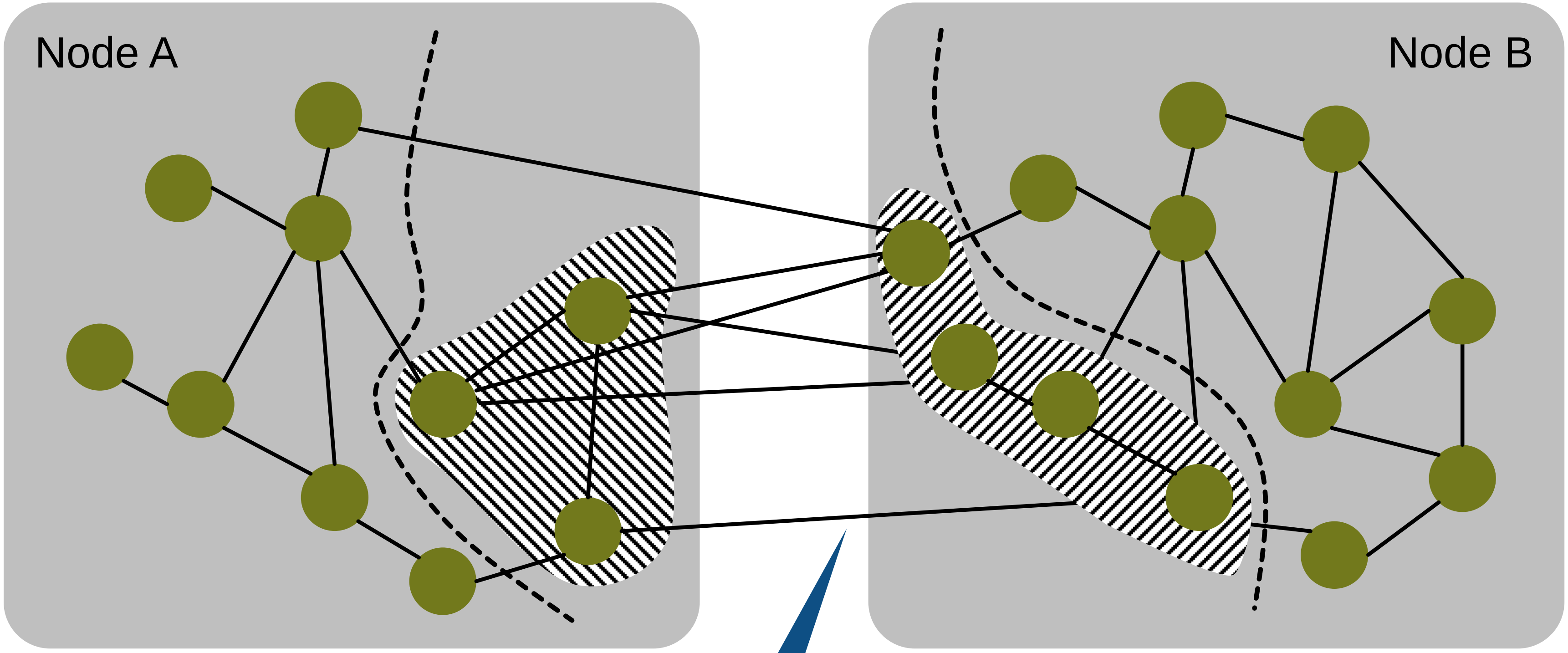

Vertices must be appropriately relocated to enable execution of a hardware transaction

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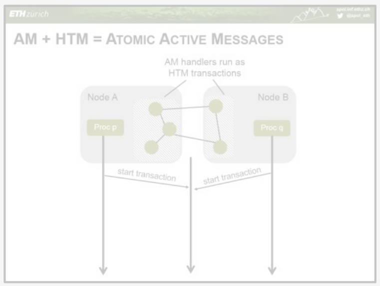

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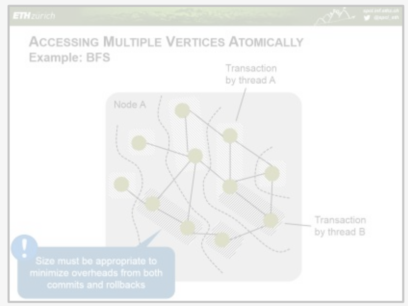

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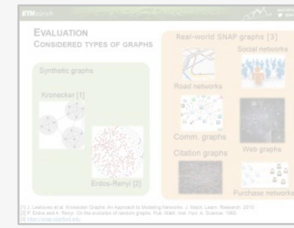

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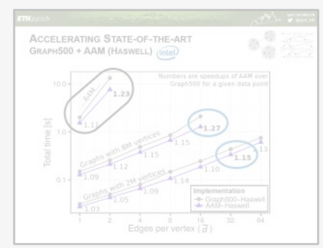

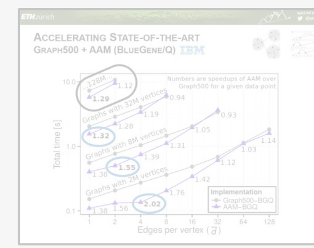

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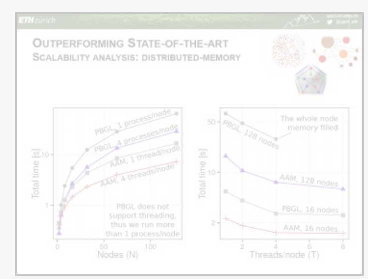
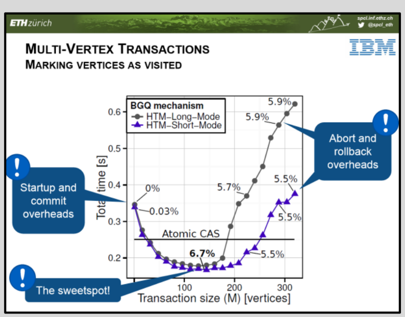
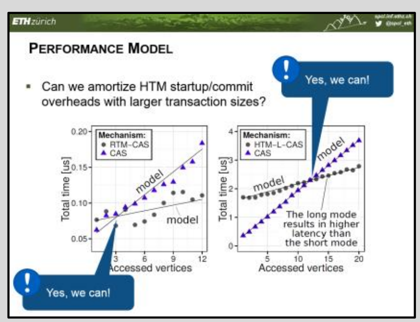


Scalability

Performance Modeling & Analysis

Haswell & BG/Q Analysis





Performance model

Performance Analysis

Research questions

How can we implement AAM handlers to run most efficiently?

What are performance tradeoffs related to HTM?

What are advantages of HTM over atomics for AAM?

What are the best transaction sizes?

Performance Analysis
Types of machines

- Evaluation on 3 machines
  - Intel Haswell server
  - InfiniBand cluster
  - IBM BlueGene/Q

Performance Analysis
Considered mechanisms

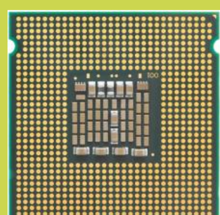
Atomics

Intel

IBM

Haswell HTM

Intel



L1 L1

32KB per core

Deployed in L1

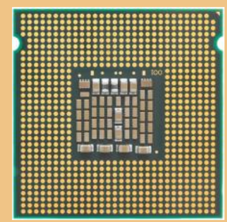
8-way associative

RTM (Restricted Transactional Memory)

HLE (Hardware Lock Elision)

BlueGene/Q HTM

IBM



L1 L1

L2

2MB per core

Deployed in L2

16-way associative

The Long Running Mode

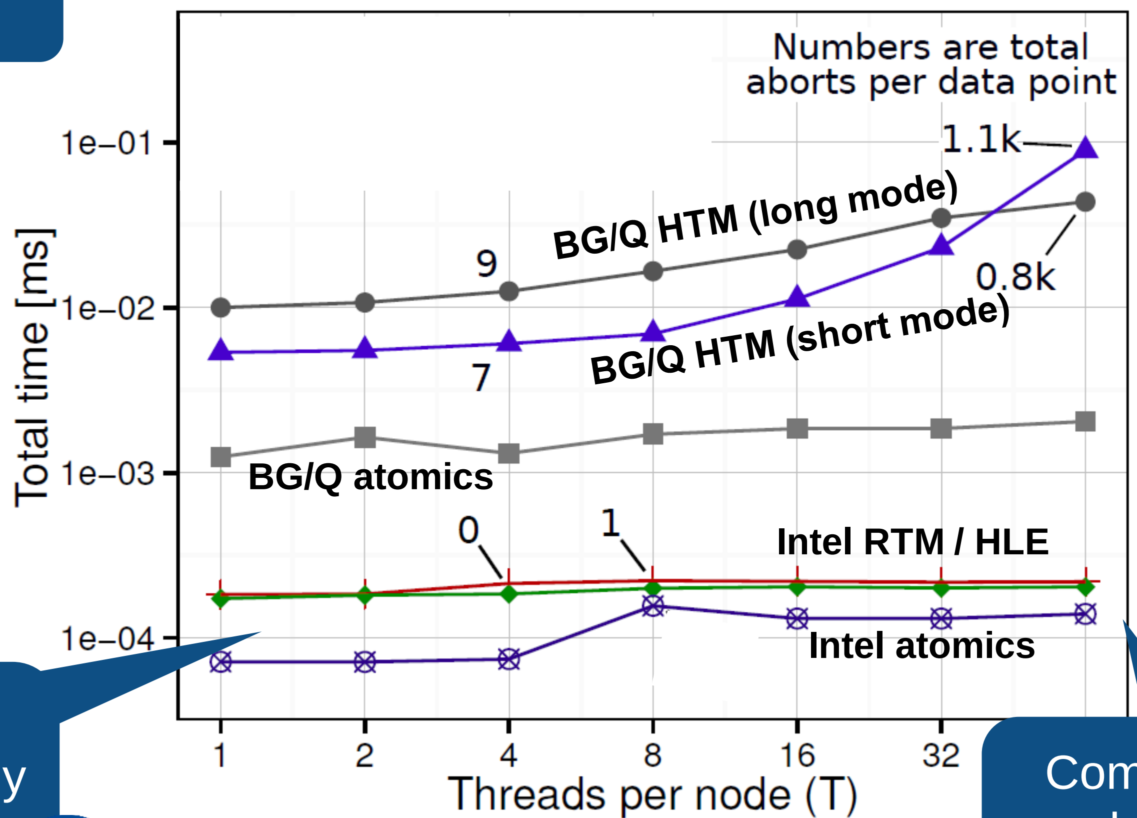
The Short Running Mode

SINGLE-VERTEX TRANSACTIONS
MARKING A VERTEX AS VISITED

Used in BFS, SSSP, ...

Very few aborts !

Lower contention
(10 racing accesses/vertex)




```
// start handler
if(!v.visited) {
 v.visited = 1;
}
// finish handler
```

Atomics (CAS) slightly faster than HTM !

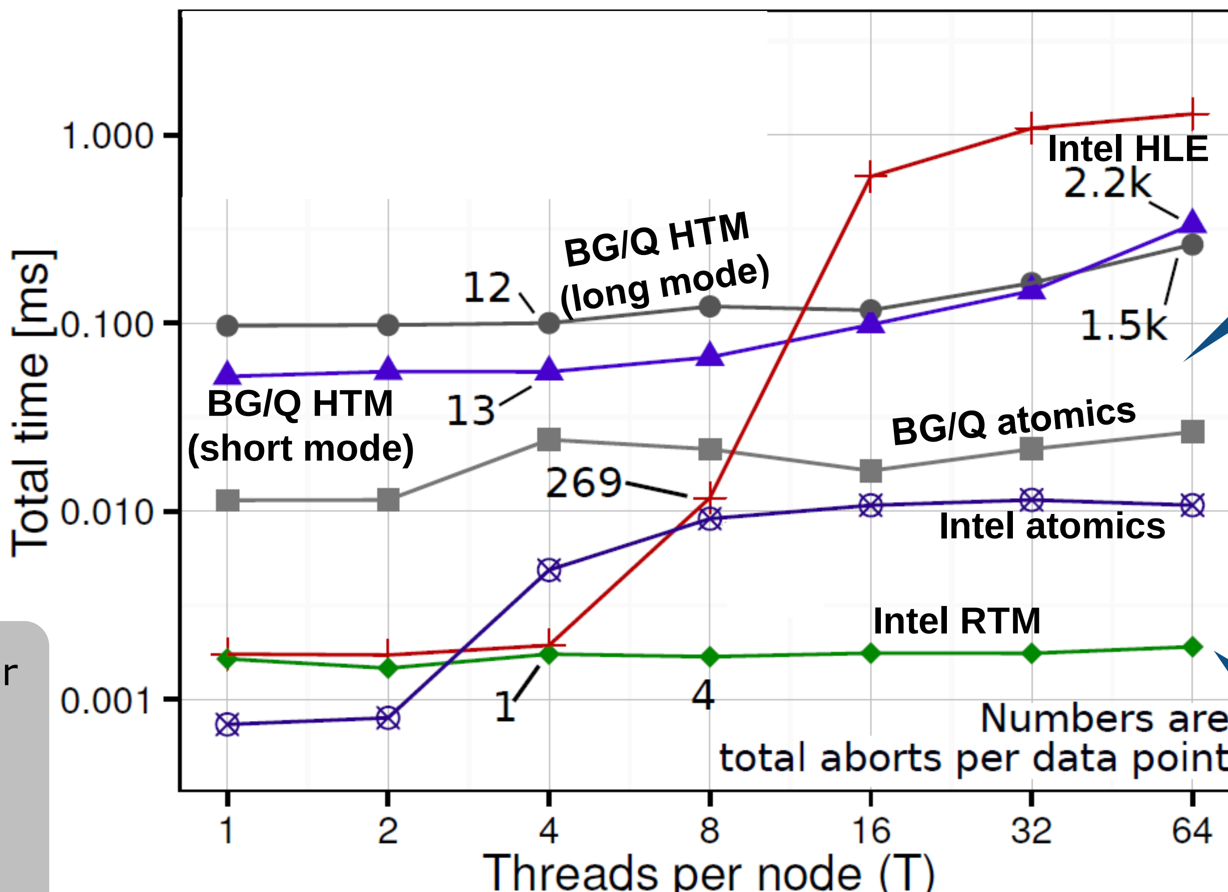
Commit overheads dominate !

Single-Vertex Transactions
Marking a vertex as visited

Used in BFS, SSSP, ...

Still very few aborts

Higher contention
(100 racing accesses/vertex)



BG/Q HTM still worse (L1 vs L2 matters!)

RTM better than atomics

```
// start handler
if(!v.visited) {
 v.visited = 1;
}
// finish
handler
```

Single-Vertex Transactions
Incrementing vertex rank

Used in PageRank

IBM intel

```
// start handler
v.rank++;
// finish handler
```

Atomics always outperform HTM

The reason: each transaction always modifies some memory cell, increasing the number of conflicts

Performance Model
Atomics vs transactions

Time to modify *N* vertices with atomics:

$$T_{AT}(N) = A_{AT}N + B_{AT}$$

Overhead per vertex

Startup overheads

Time to modify *N* vertices with a transaction

$$T_{HTM}(N) = A_{HTM}N + B_{HTM}$$

Overhead per vertex

Startup overheads

We predict that:

$$B_{AT} < B_{HTM}$$

$$A_{AT} > A_{HTM}$$

Transactions' cost grows slower

Transaction startup overheads dominate

Performance Model
Atomics vs transactions

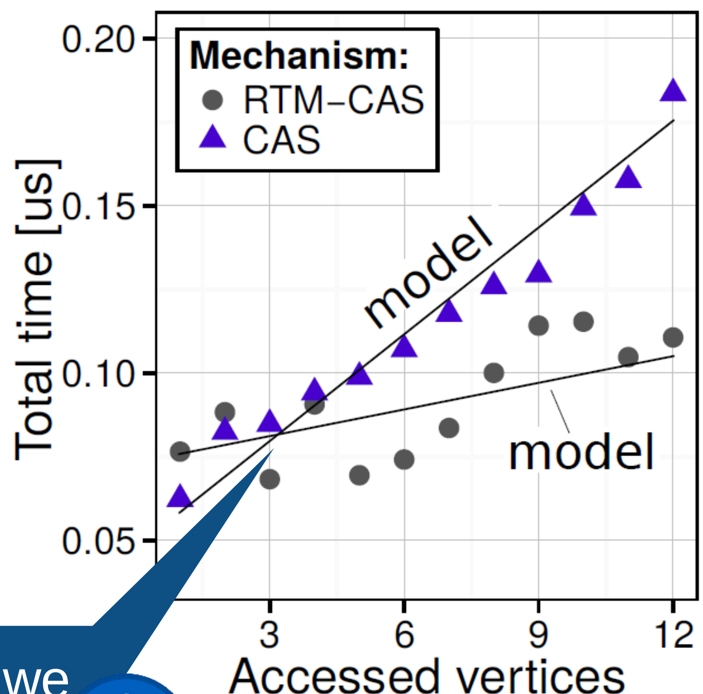
- Can we amortize HTM startup/commit overheads with larger transaction sizes?

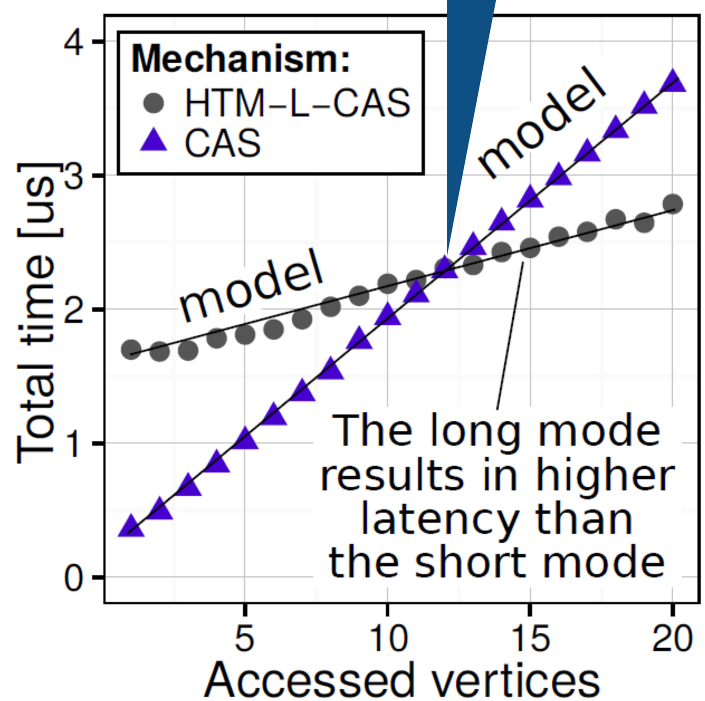
Indeed:

$$B_{AT} < B_{HTM}$$

$$A_{AT} > A_{HTM}$$

Yes, we can!

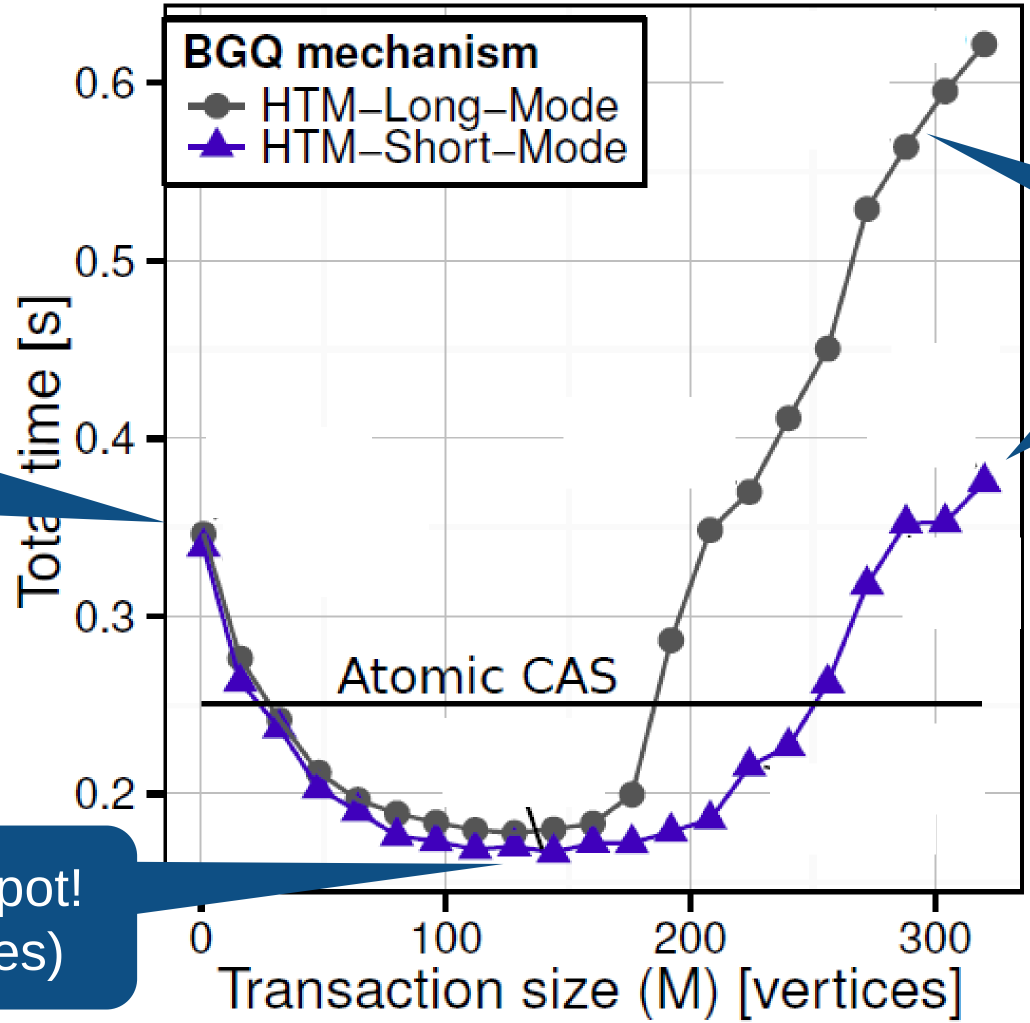




Yes, we can!

IBM

Multi-Vertex Transactions
Marking vertices as visited



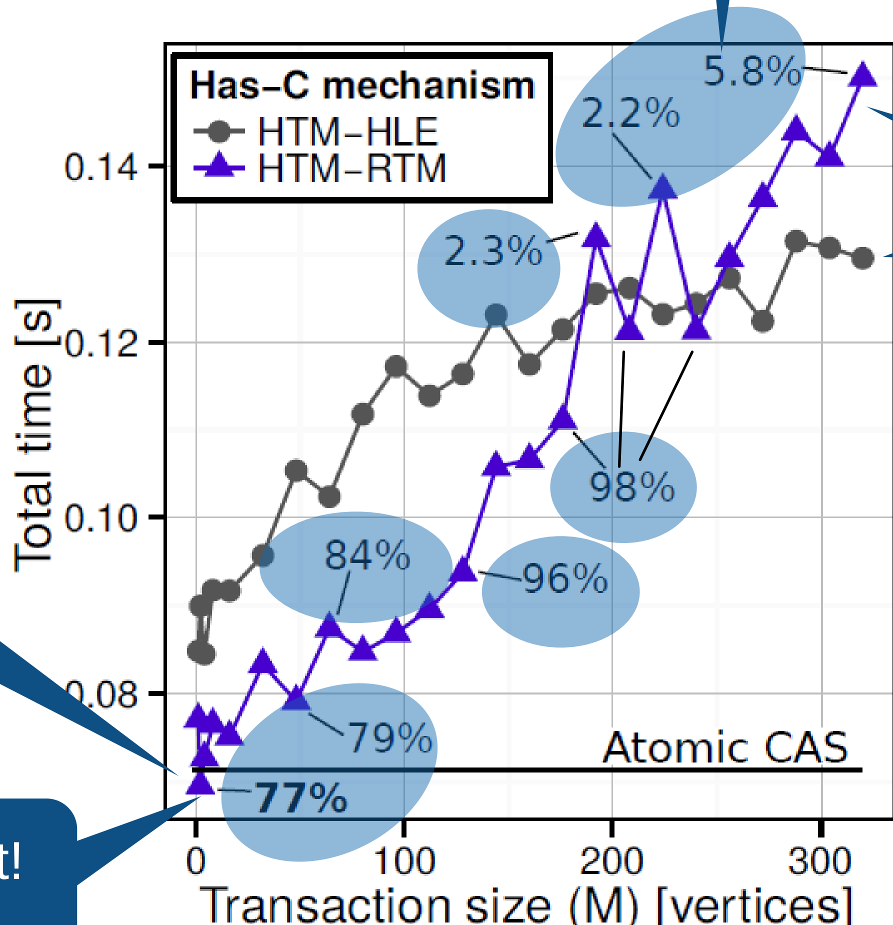
Startup and commit overheads

Abort and rollback overheads

The sweetspot! (144 vertices)

Multi-Vertex Transactions

Marking vertices as visited



Numbers: % of aborts due to HTM capacity overflows

Abort and rollback overheads

Startup and commit overheads

Majority of aborts are due to HTM capacity overflows (large cache size & associativity)

The sweetspot! (2 vertices)

Performance Analysis

Questions answered

How can we implement AAM handlers most effectively?

What are performance tradeoffs related to HTM?

What are advantages of HTM over atomics for AAM?

What are the best transaction sizes?

Performance Analysis
Questions answered

„It really depends” ☺. But... There are some regularities

Larger cache & associativity → fewer aborts & more coarsening

Larger (L2) cache → higher latency

For some algorithms (BFS) HTM is better

„May fail”

For others (PageRank) atomics give more performance

„Always succeed”

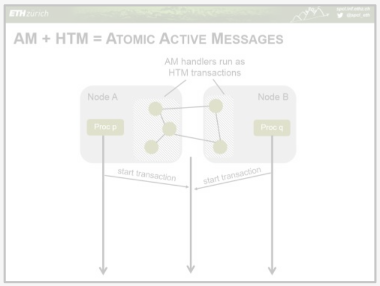
AAM establishes a whole hierarchy of algorithms; check the paper ☺

Same for other graphs

Size for BG/Q ~100 > Size for Haswell ~10

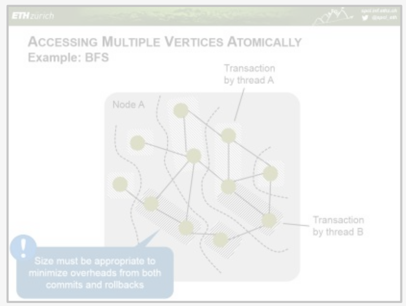
OVERVIEW OF OUR RESEARCH

AAM Design



Active Messages + HTM

Coarsening & coalescing



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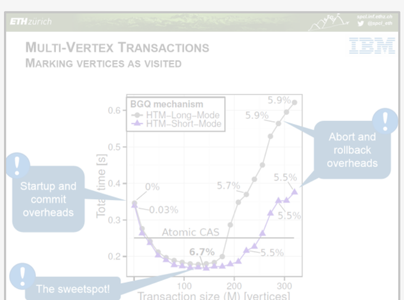
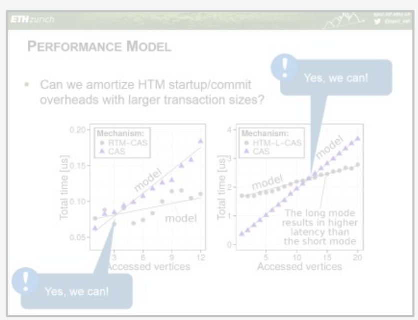
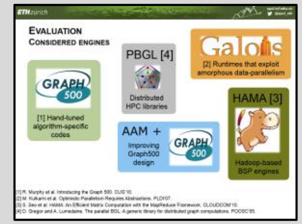
Haswell & BG/Q Analysis

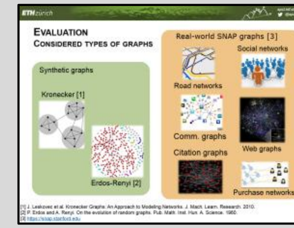




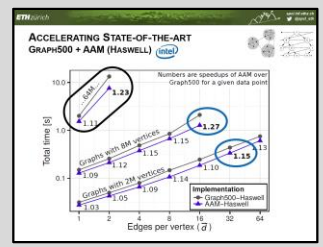
Performance model

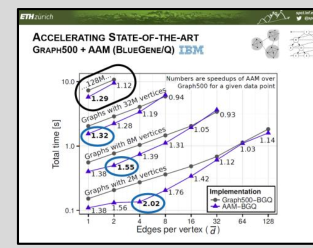
Evaluation



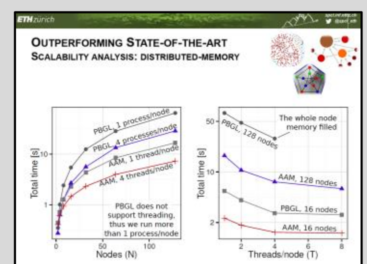


Considered engines and graphs





Accelerating state-of-the-art



Scalability

Evaluation
Considered engines

PBGL [4]

Distributed HPC libraries

Galois

[2] Runtimes that exploit amorphous data-parallelism

GRAPH 500

[1] Hand-tuned algorithm-specific codes

HAMA [3]

Hadoop-based BSP engines

AAM + GRAPH 500

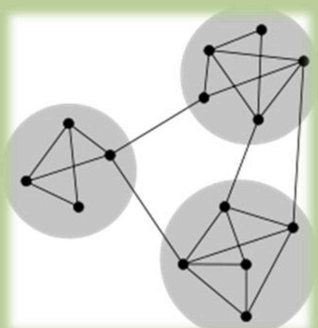
Improving Graph500 design

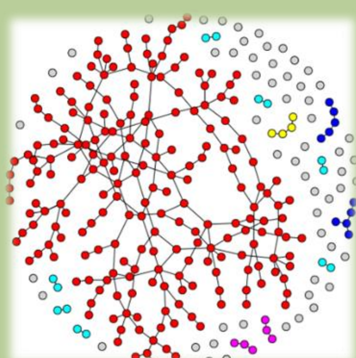
[1] R. Murphy et al. Introducing the Graph 500. CUG'10.
[2] M. Kulkarni et al. Optimistic Parallelism Requires Abstractions. PLDI'07.
[3] S. Seo et al. HAMA: An Efficient Matrix Computation with the MapReduce Framework. CLOUDCOM'10.
[4] D. Gregor and A. Lumsdaine. The parallel BGL: A generic library for distributed graph computations. POOSC'05.

Evaluation
Considered types of graphs

Synthetic graphs

Kronecker [1]





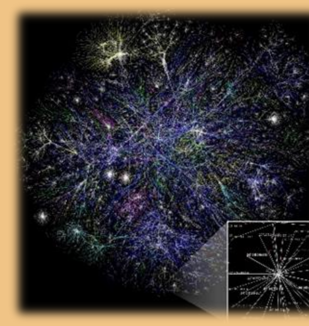
Erdös-Rényi [2]

Real-world SNAP graphs [3]

Road networks

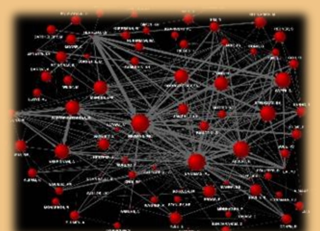
Social networks

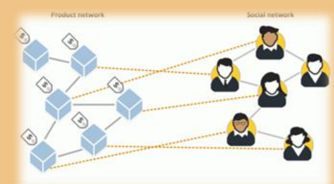
Comm. graphs



Web graphs

Citation graphs

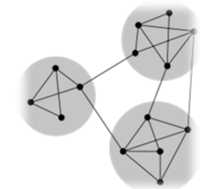


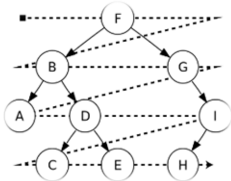


Purchase networks

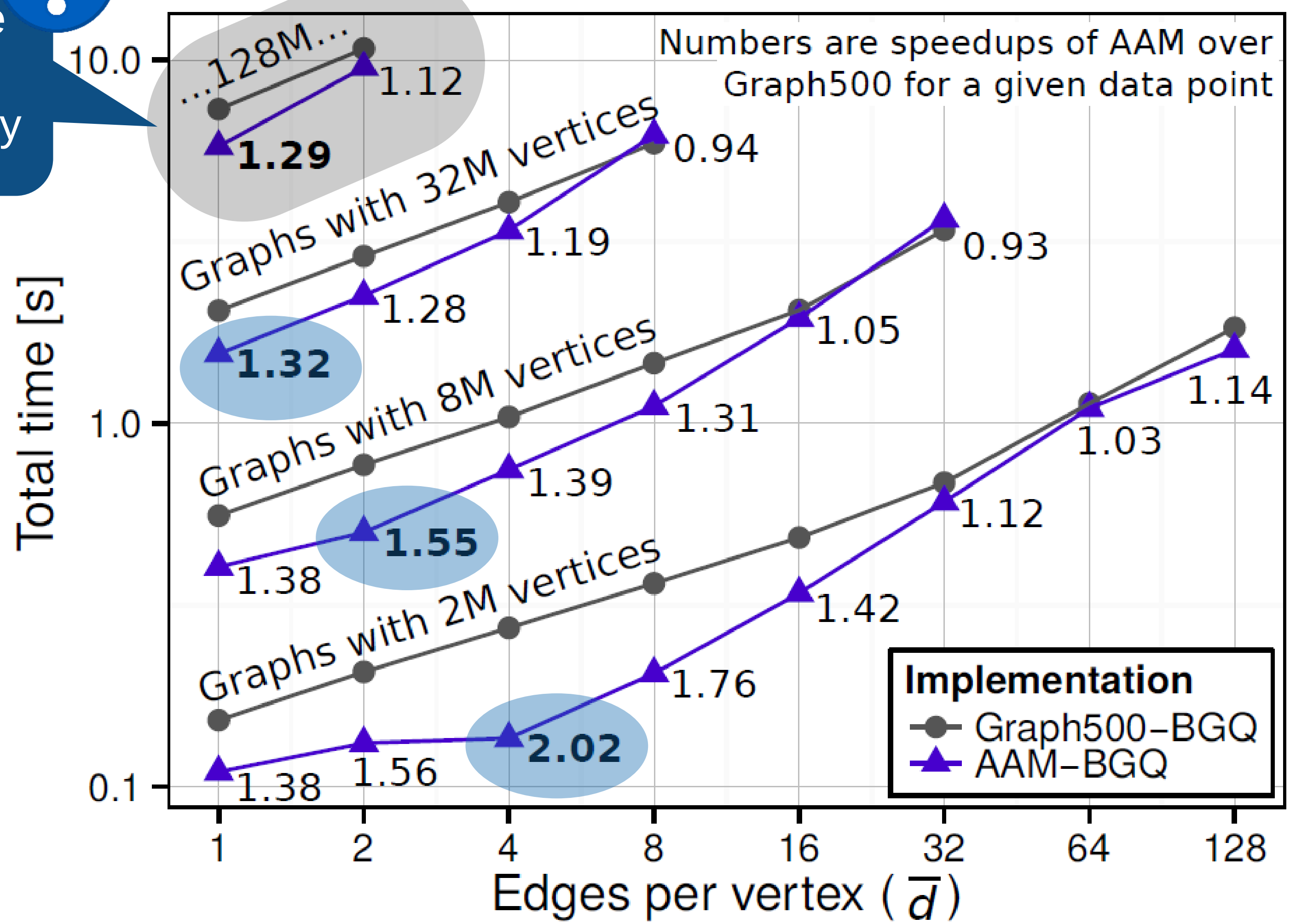
[1] J. Leskovec et al. Kronecker Graphs: An Approach to Modeling Networks. J. Mach. Learn. Research. 2010.
[2] P. Erdos and A. Renyi. On the evolution of random graphs. Pub. Math. Inst. Hun. A. Science. 1960.
[3] https://snap.stanford.edu

ACCELERATING STATE-OF-THE-ART GRAPH500 + AAM (BLUEGENE/Q)



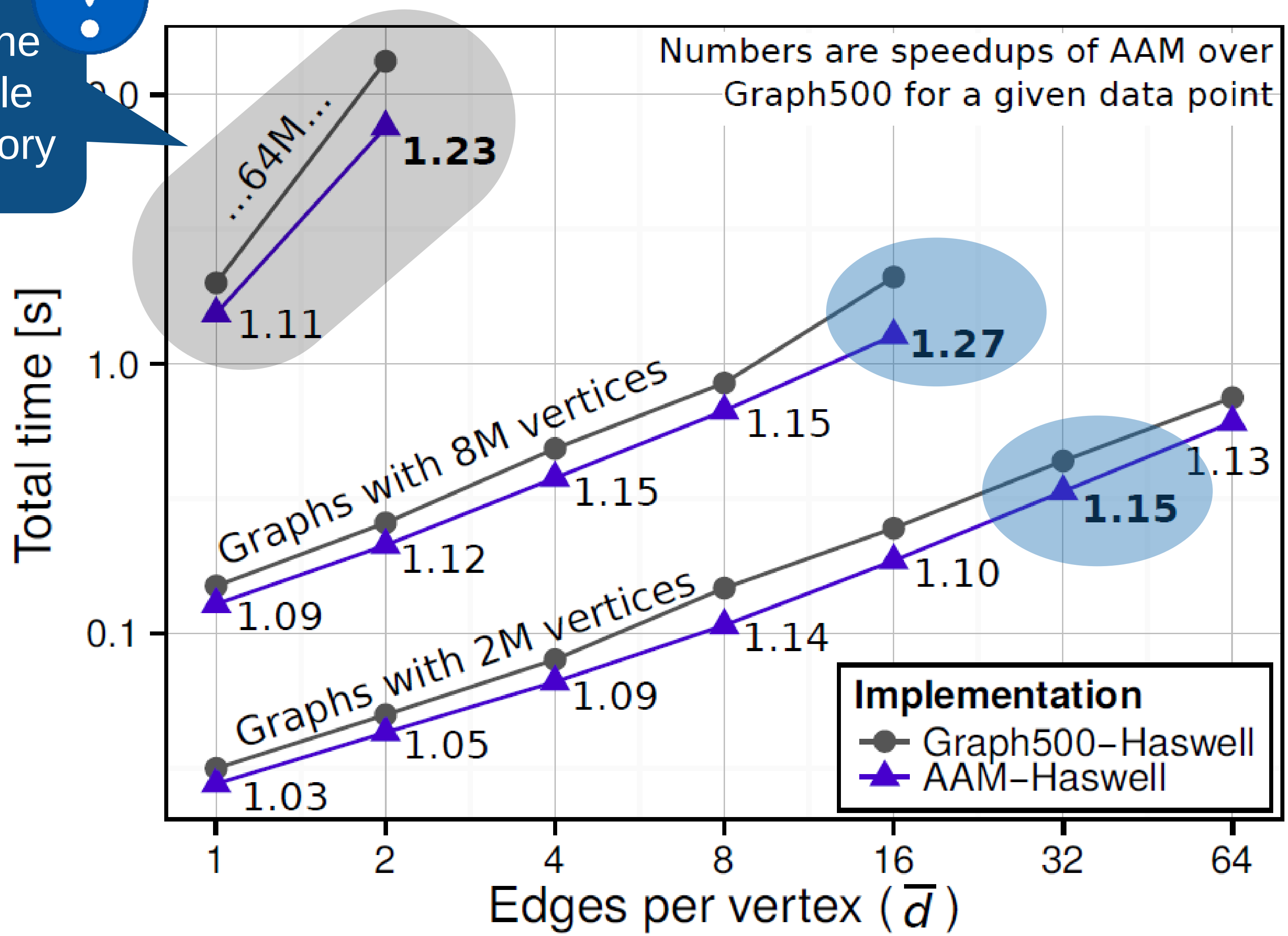


Fill the whole memory



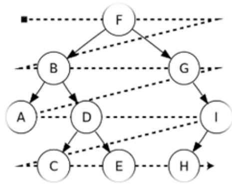
Accelerating State-of-the-Art Graph500 + AAM (Haswell)

Fill the whole memory



OUTPERFORMING STATE-OF-THE-ART

SNAP



Input graph properties					BG/Q analysis			Haswell analysis					
Type	ID	Name	$\|V\|$	$\|E\|$	S over g500 ($M = 24$)	M	S over g500	S over g500 ($M = 2$)	S over Galois ($M = 2$)	M	S over g500	S over Galois	S over HAMA
Comm. networks (CNs)	cWT	wiki-Talk	2.4M	5M	2.82	48	3.35	0.91	1.22	6	0.96	1.28	344
	cEU	email-EuAll	265k	420k	3.67	32	4.36	0.76	0.88	4	0.97	1.12	1448
Social networks (SNs)	sLV	soc-LiveJ.	4.8M	69M	1.44	12	1.56	1.05	1.1	3	1.07	1.12	$> 10^4$
	sOR	com-orkut	3M	117M	1.22	20	1.27	1.06	0.69	4	1.13	0.74	$> 10^4$
	sLJ	com-lj	4M	34M	1.44	12	1.54	1.03	1.03	4	1.04	1.04	603
	sYT	com-youtube	1.1M	2.9M	1.67	8	1.84	0.96	1.1	5	0.98	1.11	670
	sDB	com-dblp	317k	1M	1.33	8	1.80	≈ 1	2.5	2	≈ 1	2.53	2160
	sAM	com-amazon	334k	925k	1.14	8	1.62	1.04	1.64	2	1.04	1.64	1426
Purchase network (PNs)	pAM	amazon0601	403k	3.3M	1.45	8	1.91	≈ 1	1.25	3	1.03	1.30	618
Road networks (RNs)	rCA	roadNet-CA	1.9M	5.5M	≈ 1	2	1.59	1.33	1.74	8	1.38	1.80	$> 10^4$
	rTX	roadNet-TX	1.3M	3.8M	≈ 1	2	1.53	1.29	1.89	6	1.42	2.08	$> 10^4$
	rPA	roadNet-PA	1M	3M	≈ 1	2	1.52	≈ 1	2.00	9	1.07	2.16	$> 10^4$
Citation graphs (CGs)	ciP	cit-Patents	3.7M	16.5M	1.16	8	1.57	1.01	1.26	2	1.01	1.26	1875
Web graphs (WGs)	wGL	web-Google	875k	5.1M	1.78	12	2.08	0.98	1.26	6	1.06	1.35	365
	wBS	web-BerkStan	685k	7.6M	1.91	24	1.91	0.93	1.31	5	1.07	1.40	755
	wSF	web-Stanford	281k	2.3M	1.89	24	1.89	0.98	1.54	5	1.07	1.58	1077

OUTPERFORMING STATE-OF-THE-ART

SNAP

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[illegible] (SNs)	sLV	soc-LiveJ.	4.8M	69M	1.44	12	1.56	1.05	1.1	3	1.07	1.12	$> 10^4$
	sOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	sYT	com-youtube	1.1M	2.9M	1.67	8	1.54	[illegible]	1.1	5	[illegible]	[illegible]	[illegible]
	sDB	com-dblp	317k	1M	1.33	8	1.60	≈1	2.5	2	≈1	2.53	2160
	sAM	[illegible]	[illegible]	[illegible]	1.14	[illegible]	[illegible]	1.04	1.64	[illegible]	[illegible]	[illegible]	1426
Pur[illegible] network (PNs)	pAM	amazon0601	[illegible]	[illegible]	1.45	8	[illegible]	[illegible]	1.26	[illegible]	[illegible]	[illegible]	618
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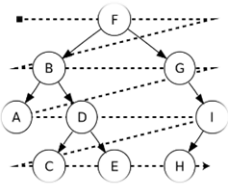
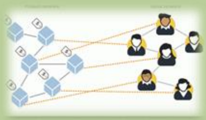
☺ No, you don't have to read it. All details are in the paper. Here: just a summary.

OUTPERFORMING STATE-OF-THE-ART

HASWELL



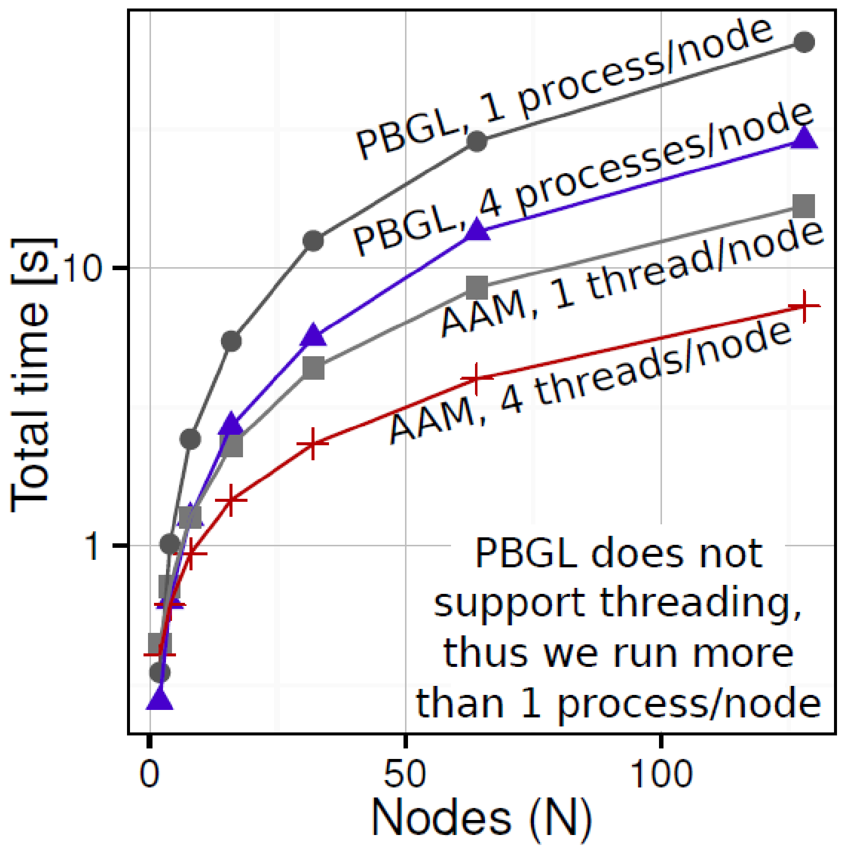



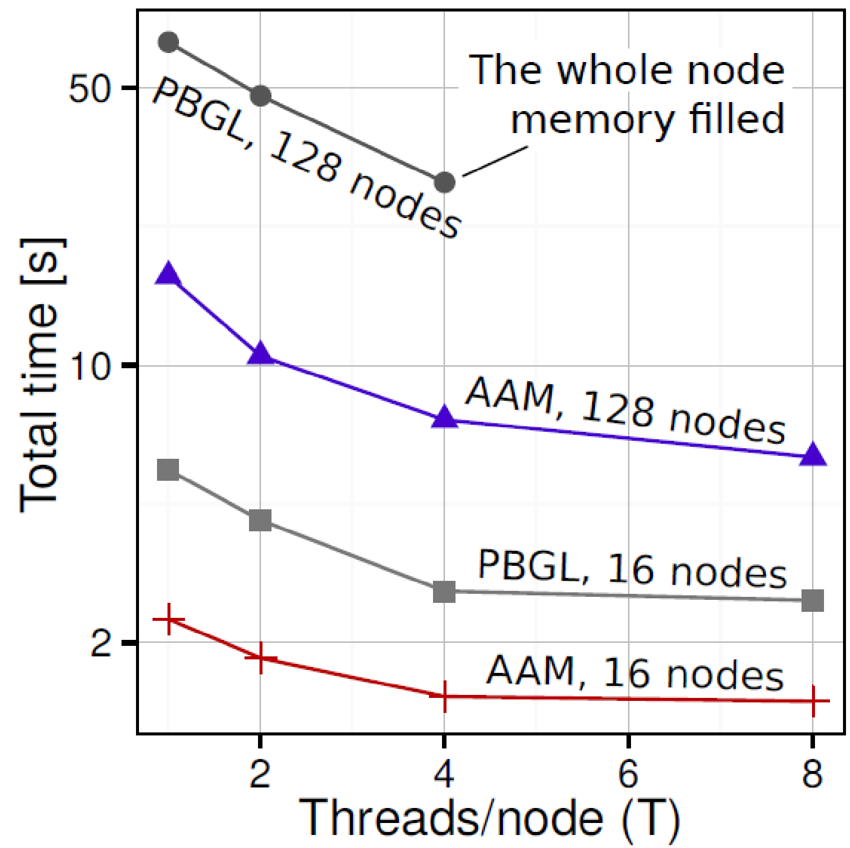


Average overall speedup (geometric mean) over Graph500: 1.07, Galois: 1.40, HAMA: ~1000

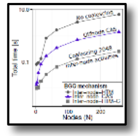
1.85x on average, up to 4.3x

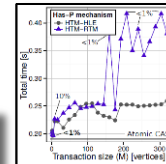
Outperforming State-of-the-Art
Scalability analysis: distributed-memory

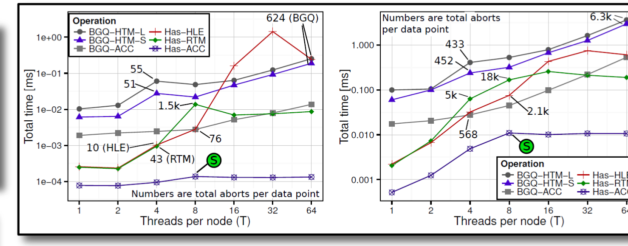


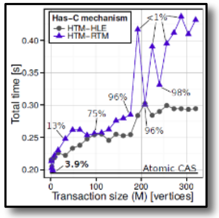


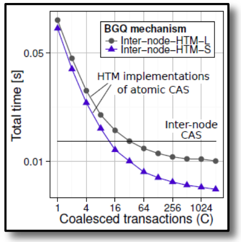
OTHER ANALYSES

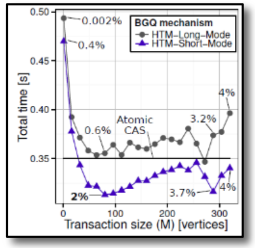


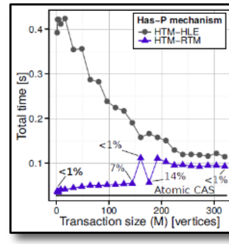


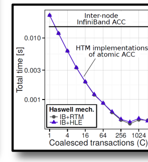


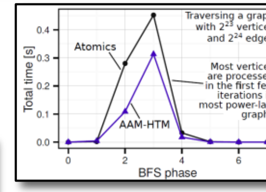


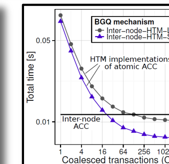


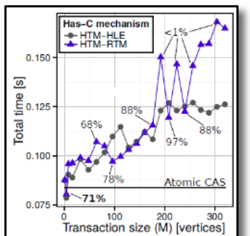


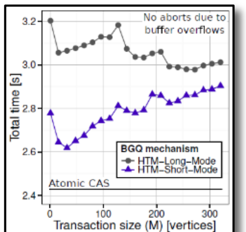


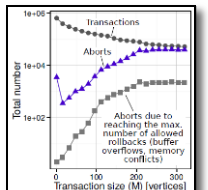


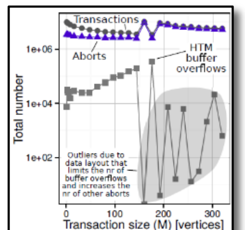


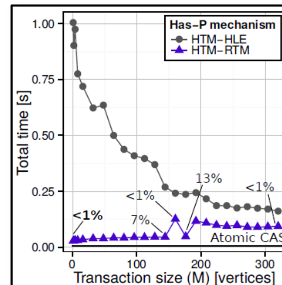






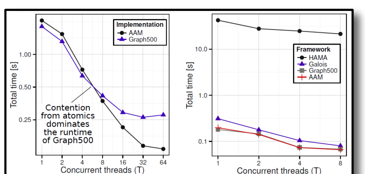


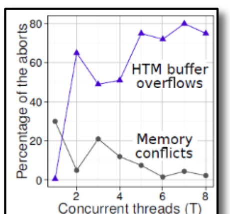


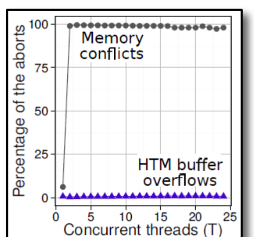


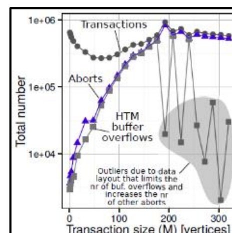
Aborts due to:

		Memory conflicts	Buffer overflows	Other reasons
10 ops	Has-RTM	1,520	1	0
	BGQ-HTM-L	624	62	614
	BGQ-HTM-S	623	62	613
100 ops	Has-RTM	18,952	33	0
	BGQ-HTM-L	6,374	637	6,360
	BGQ-HTM-S	6,392	639	6,380



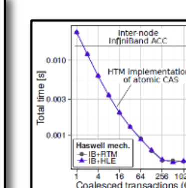


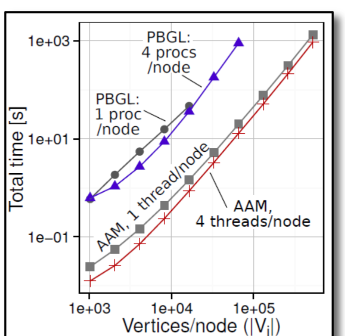


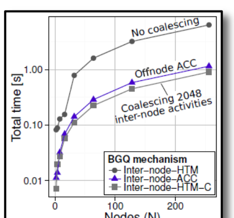


Aborts due to:

		Memory conflicts	Buffer overflows	Other reasons
10 ops	Has-RTM	2	2	0
	BGQ-HTM-L	802	3	1
	BGQ-HTM-S	1,118	46	180
100 ops	Has-RTM	2	2	0
	BGQ-HTM-L	1,539	5	1
	BGQ-HTM-S	2,242	13	2







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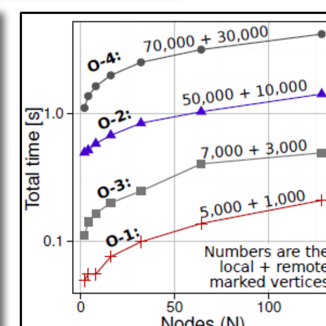
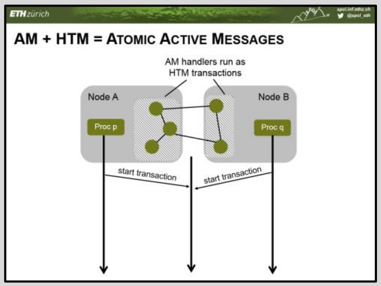
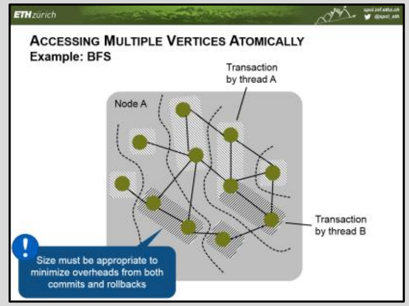


Conclusions

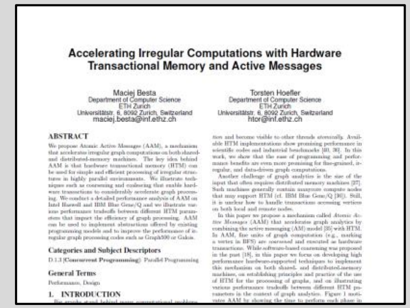
Atomic Active Messages



Combine the advantages of Active Messages and HTM

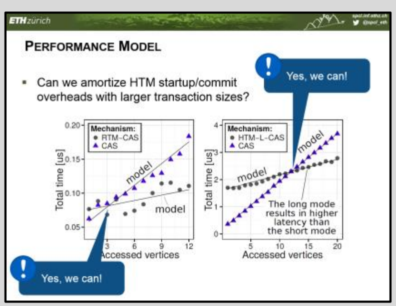


Illustrate HTM's advantages in performance, next to programmability



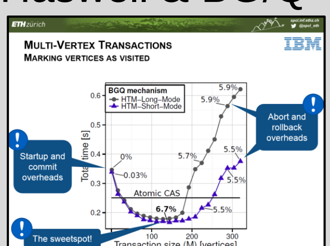
Deliver the of hierarchy of atomic messages that covers various graph algorithms

Detailed performance analysis

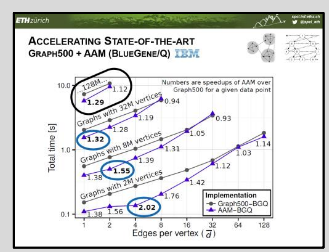


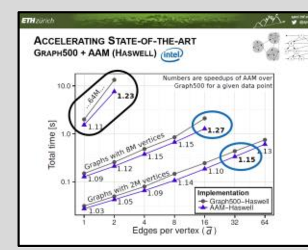
Model & analyze performance tradeoffs

Derive close-to-optimal transaction sizes for Haswell & BG/Q



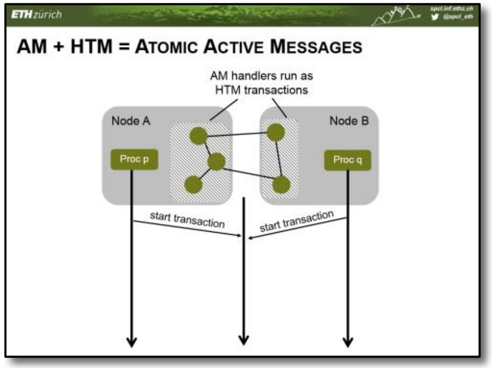
Accelerating state-of-the-art

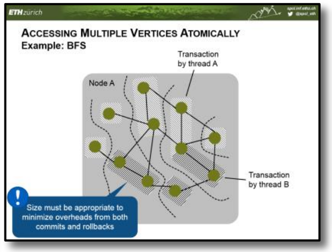


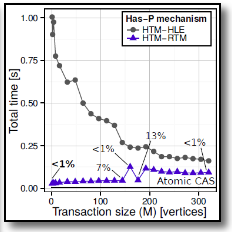


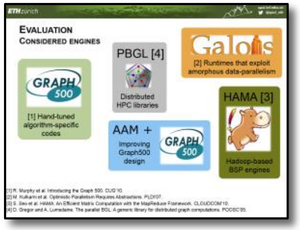
Average speedup 1.85x

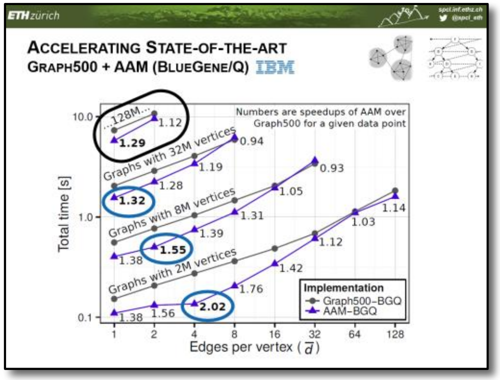
Up to 4x

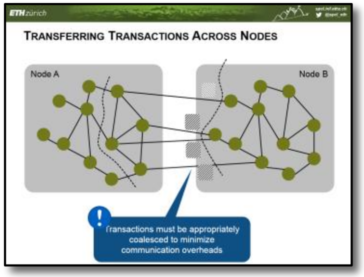


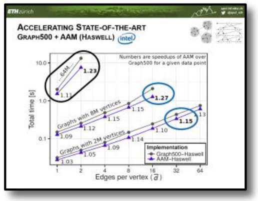


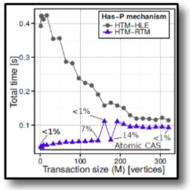


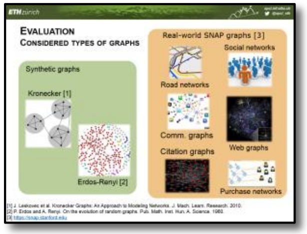




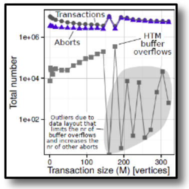


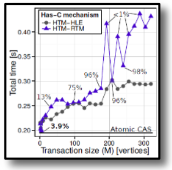


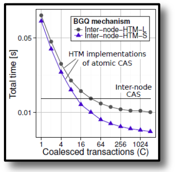


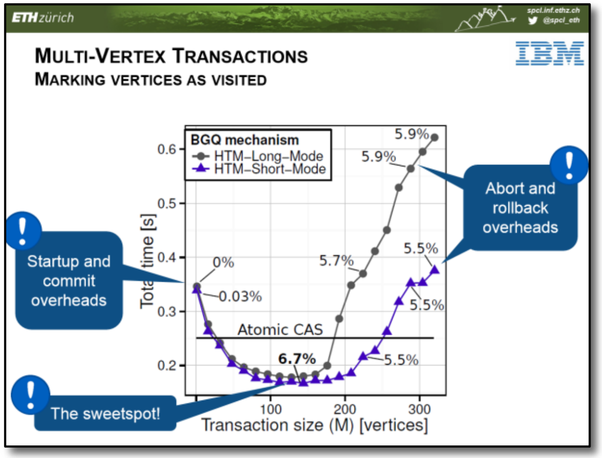


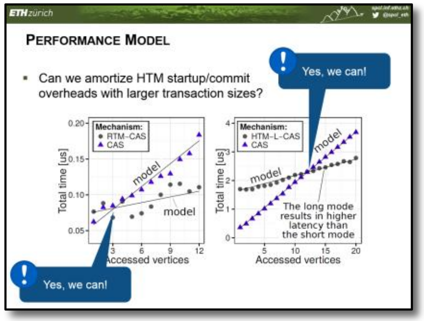
Thank you
for your attention

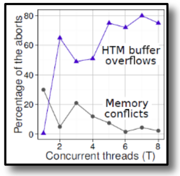


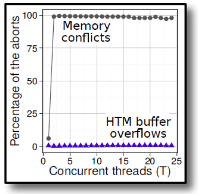


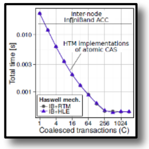


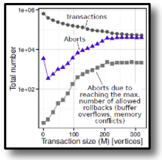


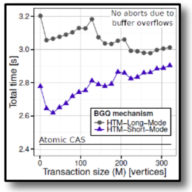


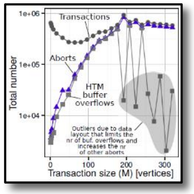


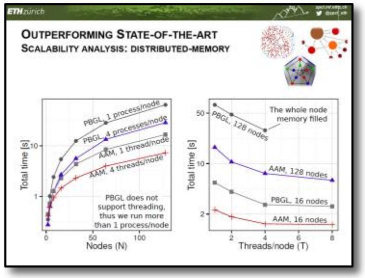




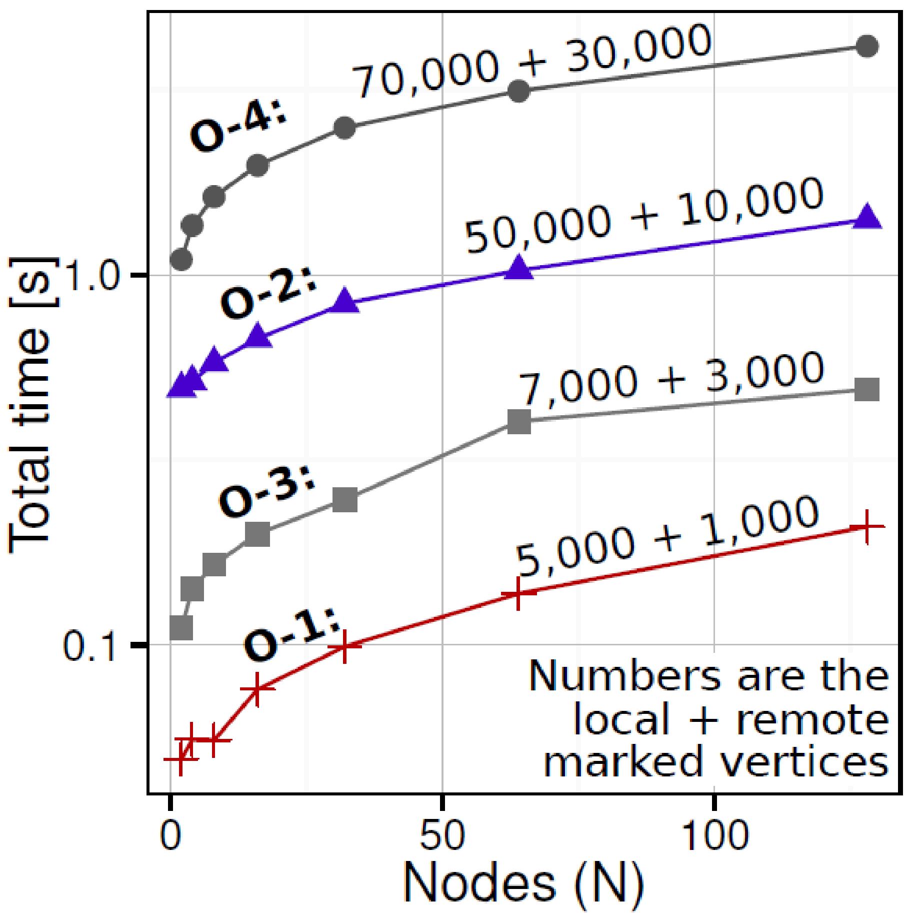








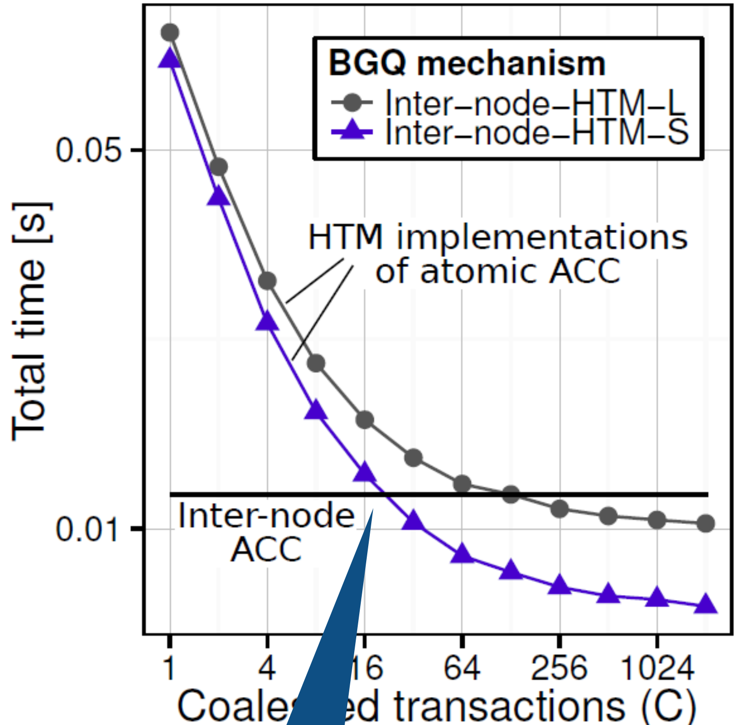
DISTRIBUTED HTM TRANSACTIONS

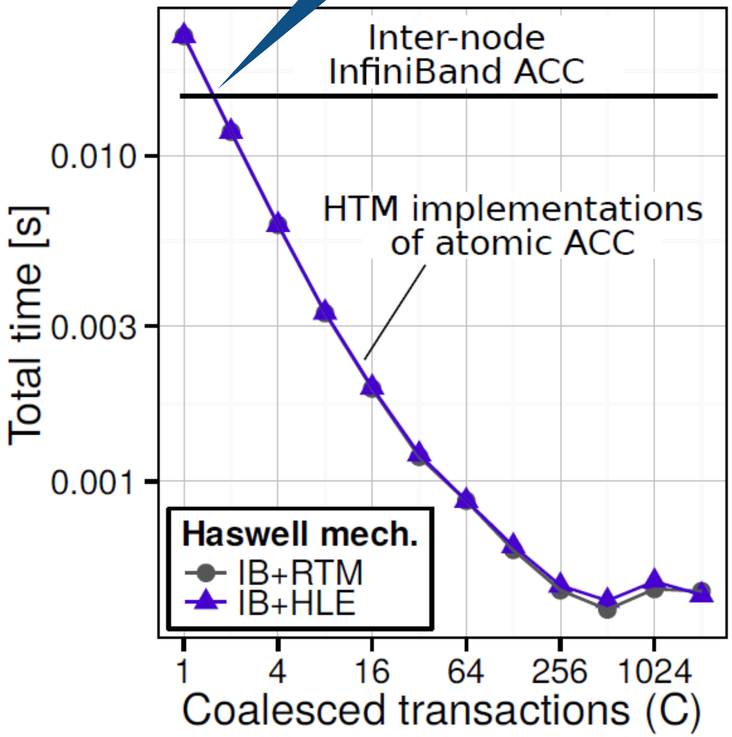


TRANSFERRING TRANSACTIONS
INCREMENTING RANKS OF VERTICES

- Can we amortize HTM transactions' transfer overheads with coalescing?

Yes, we can!





Yes, we can!

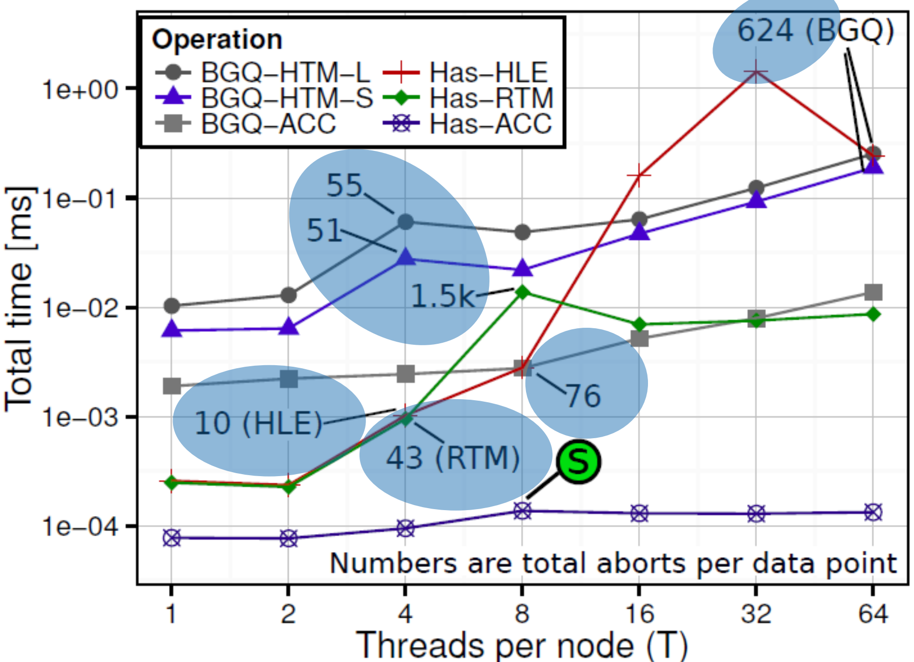
Single-Vertex Transactions
Incrementing vertex rank

Used in PageRank

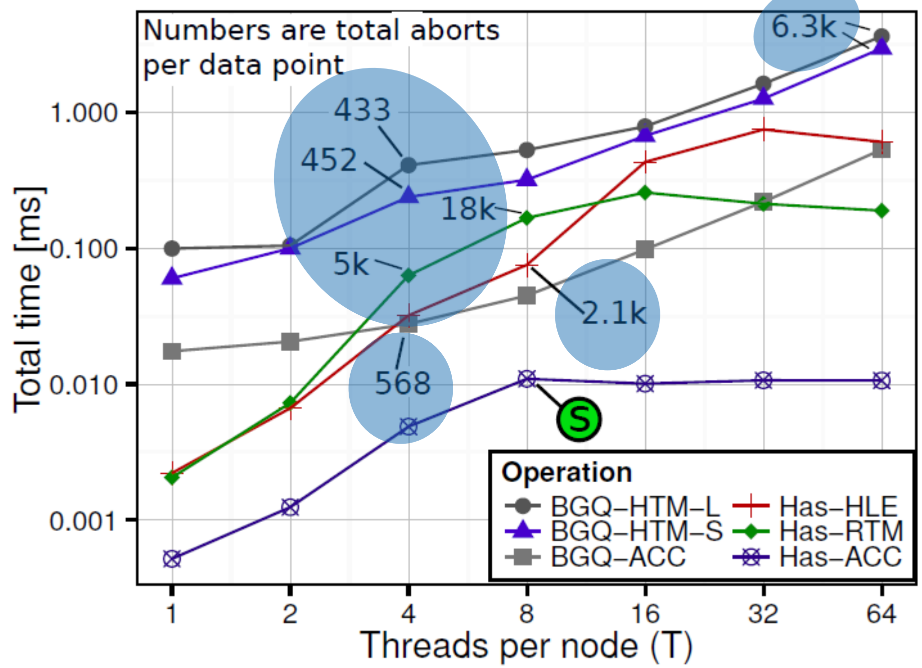
More aborts

Atomics always outperform HTM

Lower contention (10 accesses/vertex)



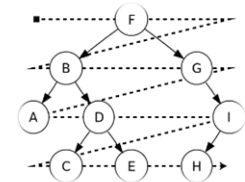
Higher contention (100 accesses/vertex)



The reason: each transaction always modifies some memory cell, increasing the number of conflicts

OUTPERFORMING STATE-OF-THE-ART

BLUEGENE/Q IBM



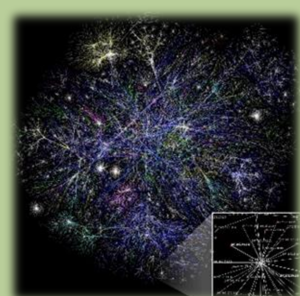
Average speedup: 1

Average overall speedup over Graph500 (geometric mean): 1.51 (1.85)

The same transaction size for all graphs

The same transaction sizes for each graph separately

Average speedup: 3.20

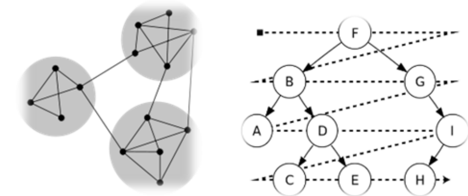


Average speedup: 1.85

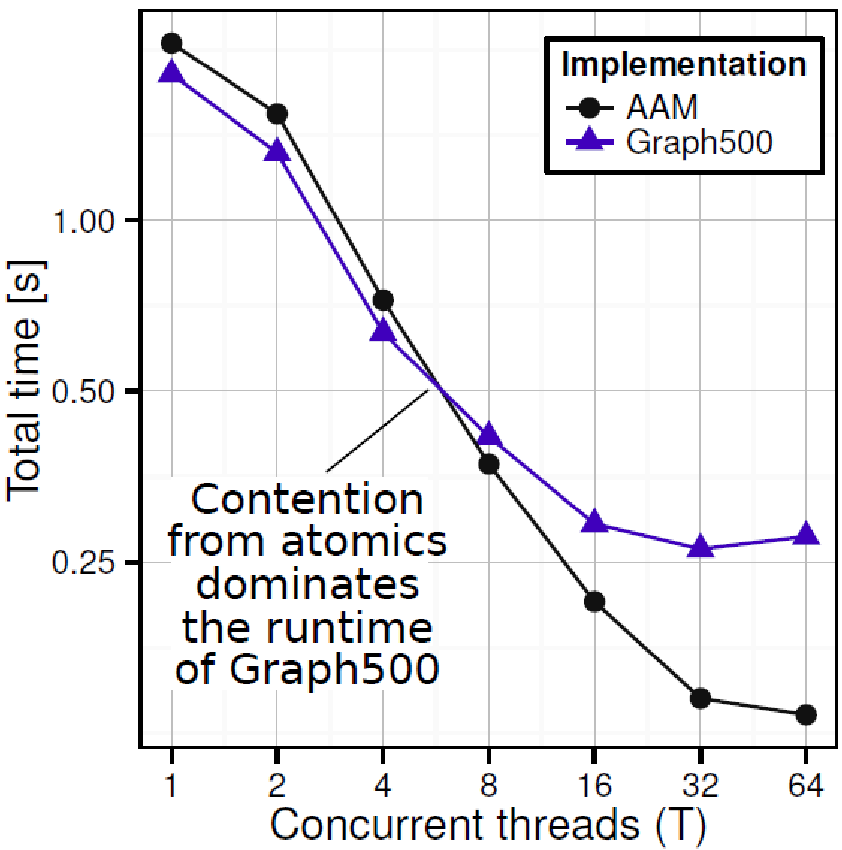
Best transaction size: ~24-100 vertices accessed

Outperforming State-of-the-Art

Scalability analysis: shared-memory



IBM



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