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T. Hoefler, M. Pueschel

Lecture 9: Finishing consensus, scalable lock study, and oblivious algorithms

Teaching assistant: Salvatore Di Girolamo

Motivational video: https://www.youtube.com/watch?v=gx2dRIQXnbs

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The simplest networking question: ping pong latency!

Rule 5: *Report if the measurement values are deterministic. For nondeterministic data, report confidence intervals of the measurement.*

- **CIs allow us to compute the number of required measurements!**
- **Can be very simple, e.g., single sentence in evaluation:**

  "We collected measurements until the 99% confidence interval was within 5% of our reported means."

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Thou shalt not trust your average textbook!

Rule 6: *Do not assume normality of collected data (e.g., based on the number of samples) without diagnostic checking.*

- **Most events will slow down performance**
  - **Heavy right-tailed distributions**
- **The Central Limit Theorem only applies asymptotically**
  - **Some papers/textbook mention "30-40 samples", don't trust them!**

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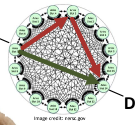
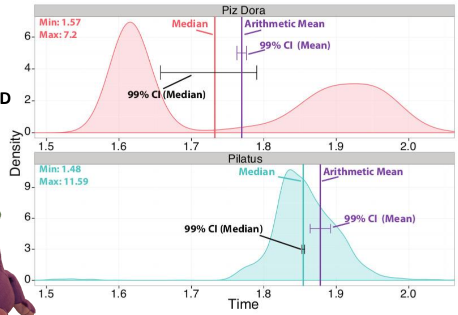
Thou shalt not trust your system!

Look what data I got!



Clearly, the mean/median are not sufficient!

Try quantile regression!



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Quantile Regression

Rule 8: *Carefully investigate if measures of central tendency such as mean or median are useful to report. Some problems, such as worst-case latency, may require other percentiles.*

- **Check Oliveira et al. "Why you should care about quantile regression". SIGARCH Computer Architecture News, 2013.**

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Administrivia

- **Final project presentation: last Monday 12/17 during lecture**
  - Report will be due in January!

    Starting to write early is very helpful --- write – rewrite – rewrite (no joke!)
  - Coordinate your talk! You have 10 minutes (8 talk + 2 Q&A)

    What happened since the intermediate report?

    Focus on the key aspects (time is tight)!

    Try to wrap up – only minor things left for final report.

    Engage the audience ☺
  - Send slides by Sunday night (11:59pm Zurich time) to Salvatore!

    We will use a single (windows) laptop to avoid delays when switching

    Expect only Windows (powerpoint) or a PDF viewer

    The order of talks will again be randomized for fairness

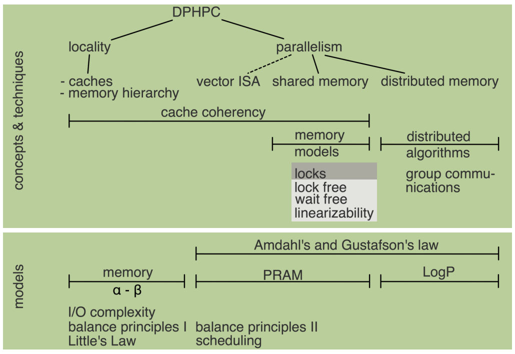
Review of last lecture(s)

- **Lock implementation(s)**
  - Advanced locks (CLH + MCS)
- **Started impossibility of wait-free consensus with atomic registers**
  - "perhaps one of the most striking impossibility results in Computer Science" (Herlihy, Shavit)
    Will continue/finish proof today as starter!
- **Theoretical background for performance**
  - Amdahl's law
  - Models: PRAM, Work/Depth, simple alpha-beta (Hockney) model
  - Simple algorithms: reduce, scan, mergesort,
  - Brent's scheduling lemma + Little's law
  - Greedy scheduling + random work stealing
- **Practical performance**
  - Roofline and balance modeling for practical performance optimization
  - Vectorization

Learning goals for today

- **Quickly recap consensus and first part of valence proof**
  - impossibility of atomic registers for wait-free consensus
  - Complete proof together
- **Case study about scalable locking**
  - Complete correctness section!
- **Oblivious algorithms**
  - How do work-depth graphs relate to practice?
- **Strict optimality**
  - Work/depth tradeoffs and bounds
- **Applications of prefix sums**
  - Parallelize seemingly sequential algorithms

DPHPC Overview



Remember: lock-free vs. wait-free

- **A locked method**
  - May deadlock (methods may never finish)
- **A lock-free method**
  - Guarantees that infinitely often **some** method call finishes in a finite number of steps
- **A wait-free method**
  - Guarantees that **each** method call finishes in a finite number of steps (implies lock-free)
- **Synchronization instructions are not equally powerful!**
  - Indeed, they form an infinite hierarchy; no instruction (primitive) in level x can be used for lock-/wait-free implementations of primitives in level z>x.

Concept: Consensus Number

- **Each level of the hierarchy has a "consensus number" assigned.**
  - Is the maximum number of threads for which primitives in level x can solve the consensus problem
- **The consensus problem:**
  - Has single function: decide(v)
  - Each thread calls it at most once, the function returns a value that meets two conditions:
    consistency: all threads get the same value
    validity: the value is some thread's input
  - Simplification: binary consensus (inputs in {0,1})

Understanding Consensus

- **Can a particular class solve n-thread consensus wait-free?**
  - A class C solves n-thread consensus if there exists a consensus protocol using **any number** of objects of class C and **any number** of atomic registers
  - The protocol has to be wait-free (bounded number of steps per thread)
  - The consensus number of a class C is the largest n for which that class solves n-thread consensus (may be infinite)
  - Assume we have a class D whose objects can be constructed from objects out of class C. If class C has consensus number n, what does class D have?

Starting simple …

- **Binary consensus with two threads (A, B)!**
  - Each thread moves until it decides on a value
  - May update shared objects
  - Protocol state = state of threads + state of shared objects
  - Initial state = state before any thread moved
  - Final state = state after all threads finished
  - States form a tree, wait-free property guarantees a finite tree
    Example with two threads and two moves each!
- **Define various states**
  - Bivalent, univalent, critical
- **Two helper lemmata**
  - Lemma 1: the initial state is bivalent
  - Lemma 2: every wait-free consensus protocol has a critical state

Atomic Registers

- **Theorem [Herlihy'91]: Atomic registers have consensus number one**
  - I.e., they cannot be used to solve even two-thread consensus! Really?
- **Proof outline:**
  - Assume arbitrary consensus protocol, thread A, B
  - Run until it reaches critical state where next action determines outcome (show that it must have a critical state first)
  - Show all options using atomic registers and show that they cannot be used to determine one outcome for all possible executions!
    1) *Any thread reads (other thread runs solo until end)*
    2) *Threads write to different registers (order doesn't matter)*
    3) *Threads write to same register (solo thread can start after each write)*

Atomic Registers

- **Theorem [Herlihy'91]: Atomic registers have consensus number one**
- **Corollary: It is impossible to construct a wait-free implementation of any object with consensus number of >1 using atomic registers**
  - "perhaps one of the most striking impossibility results in Computer Science" (Herlihy, Shavit)
  - → We **need** hardware atomics or Transactional Memory!
- **Proof technique borrowed from:**

  Impossibility of distributed consensus with one ... - ACM Digital Library
  https://dl.acm.org/citation.cfm?id=214121
  by MJ Fischer - 1985 - Cited by 4669 - Related articles
  Sep 4, 2012 - Michael J. Fischer , Nancy A. Lynch , Michael S. Paterson, **Impossibility of distributed consensus** with one faulty process, Proceedings of the ...

- **Very influential paper, always worth a read!**
  - Nicely shows proof techniques that are central to parallel and distributed computing!

Other Atomic Operations

- **Simple RMW operations (Test&Set, Fetch&Op, Swap, basically all functions where the op commutes or overwrites) have consensus number 2!**
  - Similar proof technique (bivalence argument)
- **CAS and TM have consensus number ∞**
  - Constructive proof:

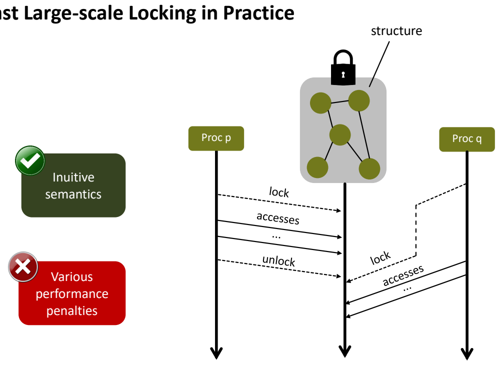
```
const int first = -1
volatile int thread = -1;
int proposed[n];

int decide(v) {
  proposed[tid] = v;
  if(CAS(thread, first, tid))
    return v; // I won!
  else
    return proposed[thread]; // thread won
}
```

  - Machines providing CAS are **asynchronous** computation equivalents of the Turing Machine
    I.e., any concurrent object can be implemented in a wait-free manner (not necessarily fast!)

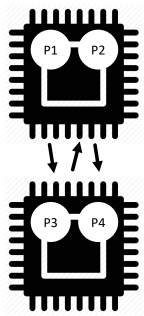
Now you know everything about parallel program correctness ☺

- **At least a lot … ;-)**
  - We'll argue more about **performance** now!
- **You have all the tools for:**
  - Efficient locks
  - Efficient lock-based algorithms
  - Reasoning about parallelism!
- **What now?**
  - Now you understand practice and will appreciate theory
    Wasn't that all too messy ☺?
  - Focus on (parallel) performance, techniques, and algorithms
- **But let's start with another case study about locks**
  - Research (best) paper published at a top-tier conference some years ago
    So you get a feeling of the field – and deepen understanding of MCS locks in practice

Case study: Fast Large-scale Locking in Practice



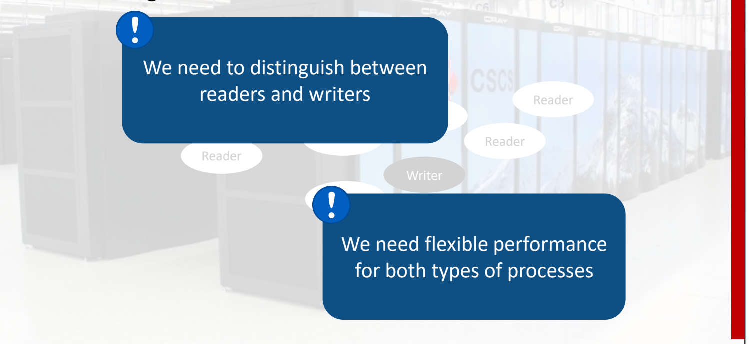
Locks: Challenges



Calciu et al.: NUMA-aware reader-writer locks, PPoPP'13

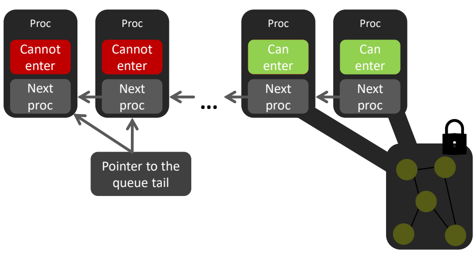
Locks: Challenges

Locks: Challenges



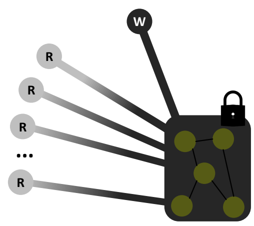
[1] V. Venkataramani et al. Tao: How facebook serves the social graph. SIGMOD'12.

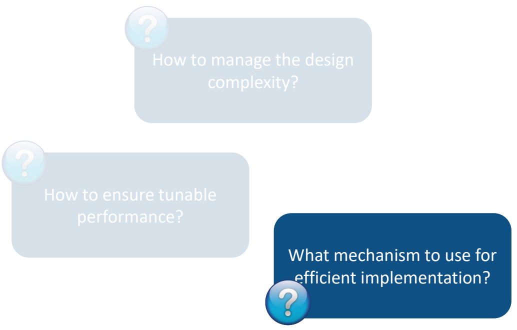
Ingredient 1 - MCS Locks



Mellor-Crummey and Scott: Algorithms for Scalable Synchronization on Shared-Memory Multiprocessors, ACM TOCS'91

Ingredient 2 - Reader-Writer Locks





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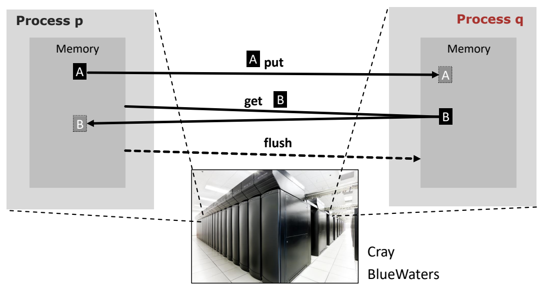
Remote Memory Access (RMA) Programming



TH, J. Dinan, R. Thakur, B. Barrett, P. Balaji, W. Gropp, K. Underwood: Remote Memory Access Programming in MPI-3, ACM TOPC'15

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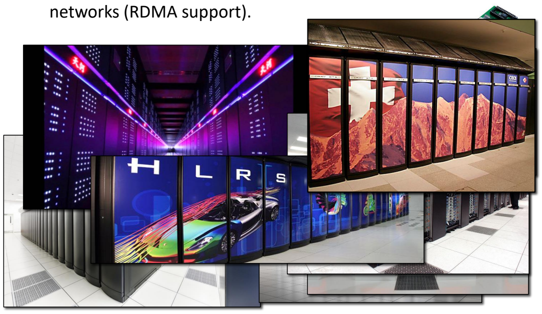
Remote Memory Access Programming

- Implemented in hardware in NICs in the majority of HPC networks (RDMA support).



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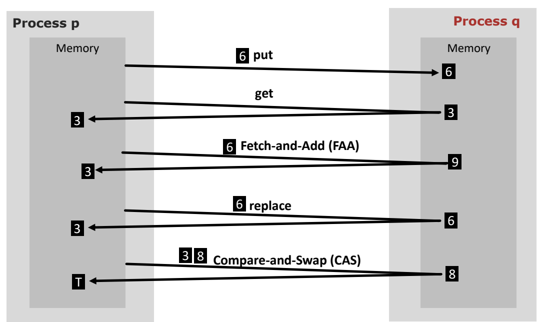
RMA-RW - Required Operations



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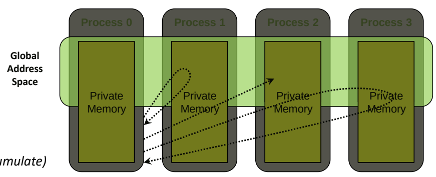
MPI RMA primer ([much] more in the recitation sessions)

- **Windows expose memory**
  - Created explicitly
- **Remote accesses**
  - Put, get
  - Atomics
    Accumulate (also atomic Put)
    Get_accumulate (also atomic Get)
    Fetch and op (faster single-word get_accumulate)
    Compare and swap
- **Synchronization**
  - Two modes: passive and active target
    We use passive target today, similar to shared memory!
    Synchronization: flush, flush_local
- **Memory model**
  - Unified (coherent) and separate (not coherent) view - it's complicated but versatile



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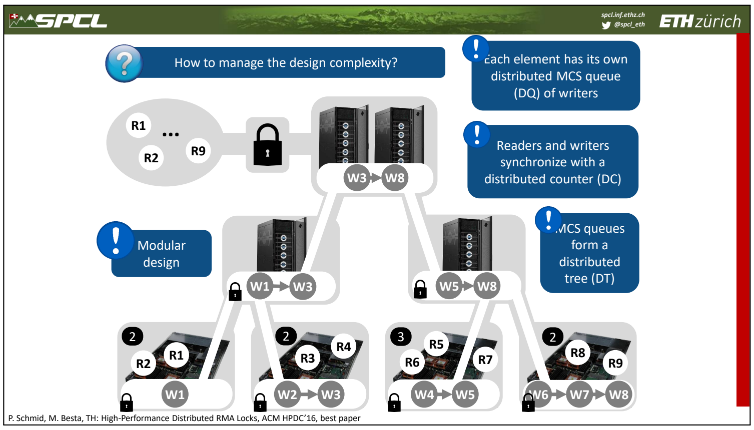
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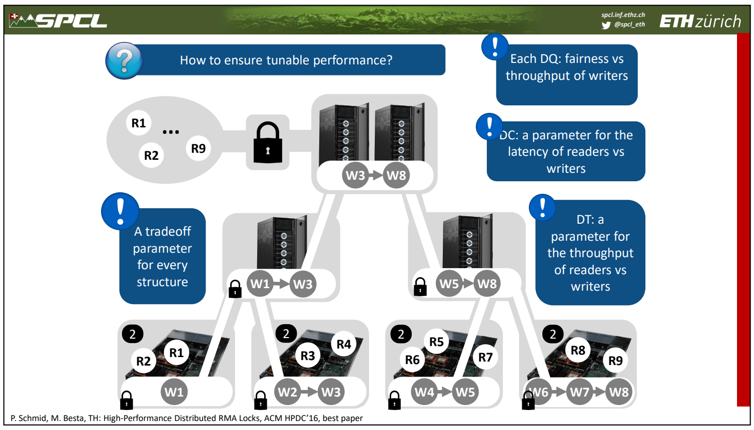
How to manage the design complexity?
Each element has its own distributed MCS queue (DQ) of writers
Readers and writers synchronize with a distributed counter (DC)
MCS queues form a distributed tree (DT)
Modular design
R1
R2
R9
W3
W8
W1
W5
2
3
R3
R4
R5
R6
R7
R8
W2
W4
W6
W7
P. Schmid, M. Besta, TH: High-Performance Distributed RMA Locks, ACM HPDC'16, best paper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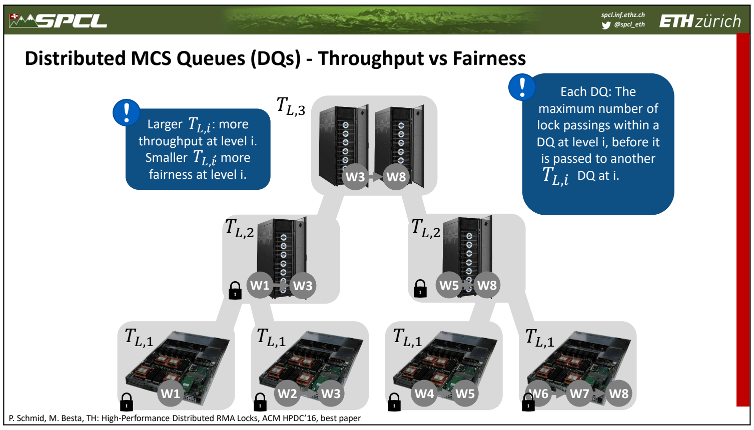
How to ensure tunable performance?
Each DQ: fairness vs throughput of writers
DC: a parameter for the latency of readers vs writers
A tradeoff parameter for every structure
DT: a parameter for the throughput of readers vs writers
R1
R2
R9
W3
W8
W1
W5
P. Schmid, M. Besta, TH: High-Performance Distributed RMA Locks, ACM HPDC'16, best paper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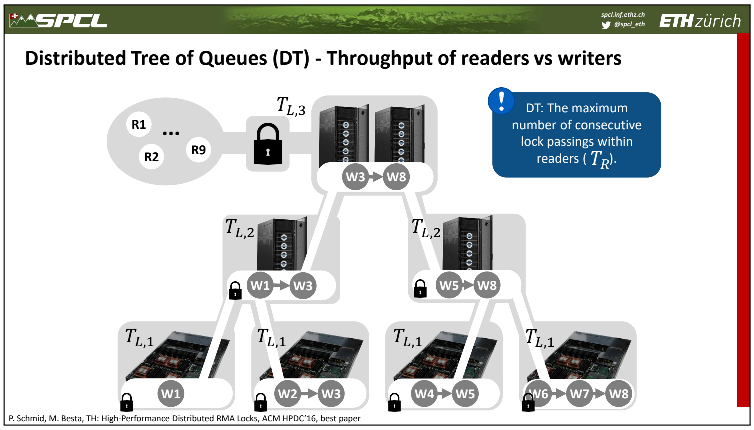
Distributed MCS Queues (DQs) - Throughput vs Fairness
Larger $T_{L,i}$: more throughput at level i. Smaller $T_{L,i}$: more fairness at level i.
Each DQ: The maximum number of lock passings within a DQ at level i, before it is passed to another $T_{L,i}$ DQ at i.
$T_{L,3}$
$T_{L,2}$
$T_{L,1}$
W1
W2
W3
W4
W5
W6
W7
W8
P. Schmid, M. Besta, TH: High-Performance Distributed RMA Locks, ACM HPDC'16, best paper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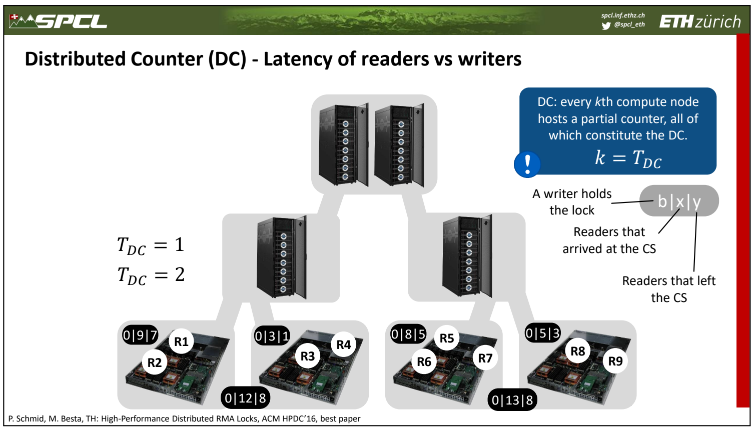
Distributed Tree of Queues (DT) - Throughput of readers vs writers
DT: The maximum number of consecutive lock passings within readers (T_R).
$T_{L,3}$
$T_{L,2}$
$T_{L,1}$
R1
R2
R9
W1
W2
W3
W4
W5
W6
W7
W8
P. Schmid, M. Besta, TH: High-Performance Distributed RMA Locks, ACM HPDC'16, best paper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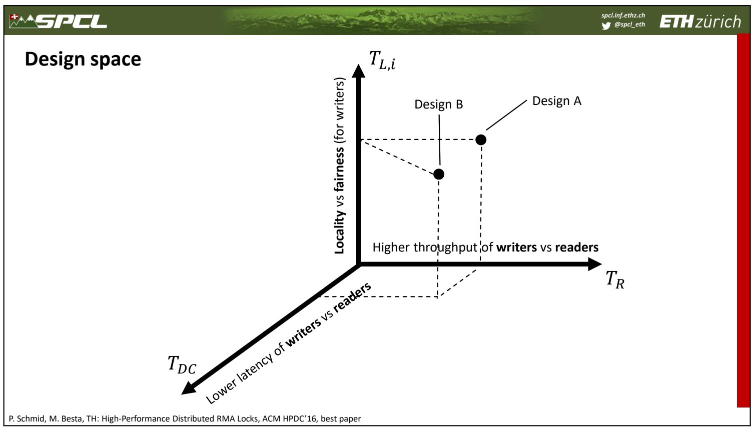
Distributed Counter (DC) - Latency of readers vs writers
DC: every kth compute node hosts a partial counter, all of which constitute the DC.
$k = T_{DC}$
b|x|y
A writer holds the lock
Readers that arrived at the CS
Readers that left the CS
$T_{DC} = 1$
$T_{DC} = 2$
0|9|7
0|3|1
0|8|5
0|5|3
0|12|8
0|13|8
R1
R2
R3
R4
R5
R6
R7
R8
R9
P. Schmid, M. Besta, TH: High-Performance Distributed RMA Locks, ACM HPDC'16, best paper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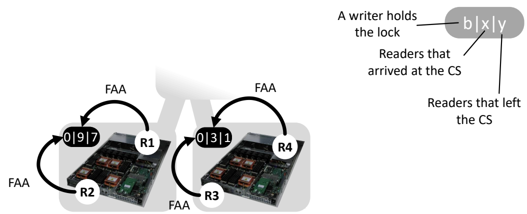
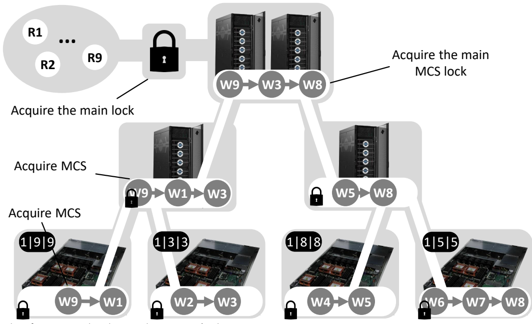
Design space
$T_{L,i}$
Locality vs fairness (for writers)
Design B
Design A
Higher throughput of writers vs readers
T_R
T_{DC}
Lower latency of writers vs readers
P. Schmid, M. Besta, TH: High-Performance Distributed RMA Locks, ACM HPDC'16, best paper

Lock Acquire by Readers

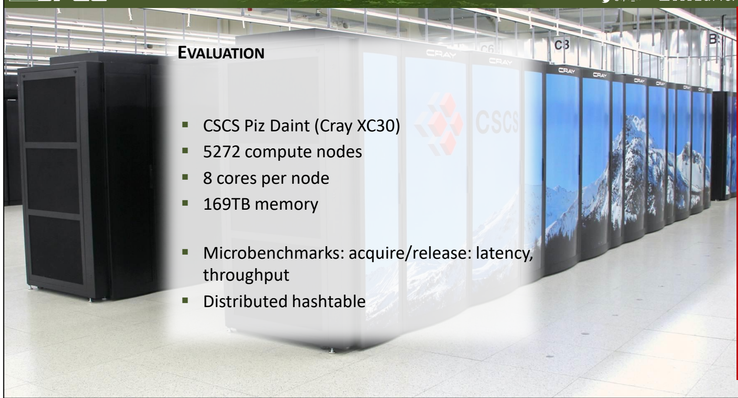
! A lightweight acquire protocol for readers: only one atomic fetch-and-add (FAA) operation



Lock Acquire by Writers



EVALUATION



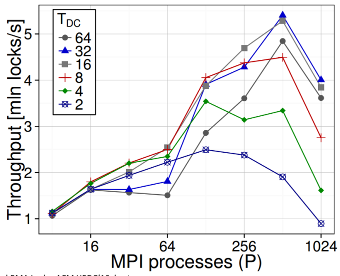
- CSCS Piz Daint (Cray XC30)
- 5272 compute nodes
- 8 cores per node
- 169TB memory

- Microbenchmarks: acquire/release: latency, throughput
- Distributed hashtable

Evaluation - Distributed Counter Analysis

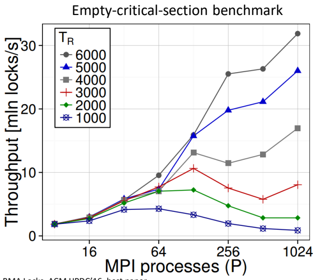
0|12|8

Throughput, 2% writers
Single-operation benchmark

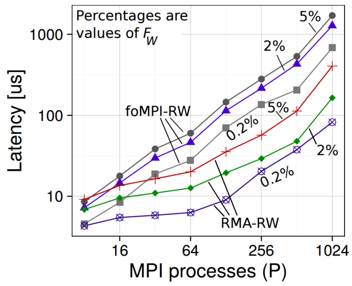


Evaluation - Reader Threshold Analysis

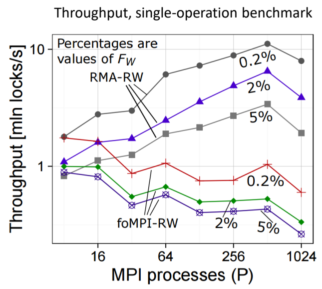
Throughput, 0.2% writers,
Empty-critical-section benchmark



Evaluation - Comparison to the State-of-the-Art

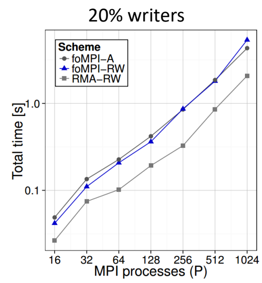


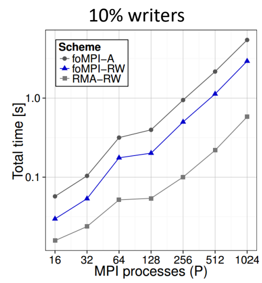
Evaluation - Comparison to the State-of-the-Art



[1] R. Gerstenberger et al. Enabling Highly-scalable Remote Memory Access Programming with MPI-3 One Sided. ACM/IEEE Supercomputing 2013.

Evaluation - Distributed Hashtable





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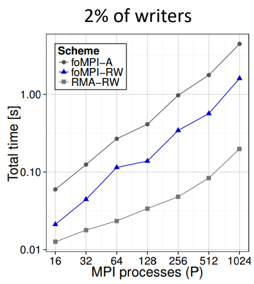

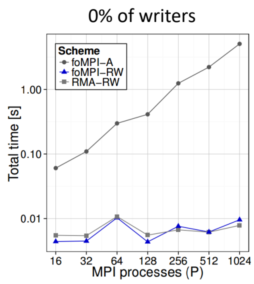

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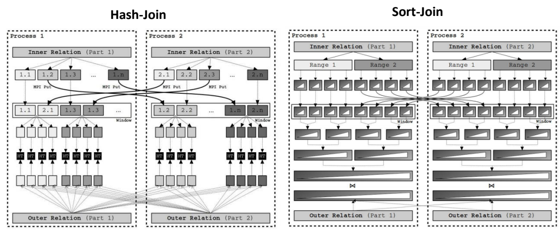
Another application area - Databases

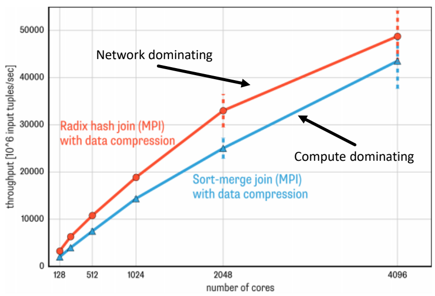
- **MPI-RMA for distributed databases?**



C. Barthels, et al., TH: Distributed Join Algorithms on Thousands of Cores presented in Munich, Germany, VLDB Endowment, Aug. 2017

Another application area - Databases

- **MPI-RMA for distributed databases on Piz Daint**



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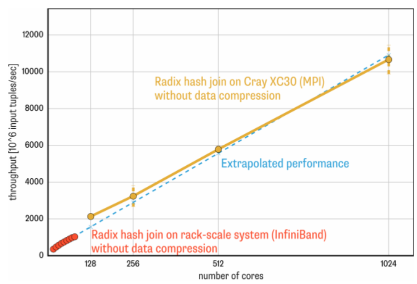


C. Barthels, et al., TH: Distributed Join Algorithms on Thousands of Cores presented in Munich, Germany, VLDB Endowment, Aug. 2017

Now on to parallel algorithms!

- **Oblivious parallel algorithms**
  - Fixed structure work-depth graphs
- **Nonoblivious parallel algorithms**
  - Data-dependent structure work-depth graphs
- **Data movement and I/O complexity**
  - Communication complexity

Work/Depth in Practice – Oblivious Algorithms

*"An algorithm is **execution-oblivious** if, for each problem size, the sequence of instructions executed, the set of memory locations read and the set of memory locations written by each executed instruction are determined by the input size and are independent of the values of the other inputs"*

Execution oblivious or not?

```
int reduce(int n, arr[n]) {
  for(int i=0; i<n; ++i)
    sum += arr[i];
}
```

```
int findmin(int n, a[n]) {
  for(int i=1; i<n; i++)
    if(a[i]<a[0]) a[0] = a[i];
}
```

```
int finditem(list_t list)
  item = list.head;
  while(item.value!=0 && item.next!=NULL)
    item=item.next;
}
```

- Quicksort?
- Prefix sum on an array?
- Simple dense matrix multiplication?
- Dense matrix vector product?
- Sparse matrix vector product?
- Queue-based breadth-first search?

Obliviousness as property of an execution

*"An algorithm is **execution-oblivious** if, for each problem size, the sequence of instructions executed, the set of memory locations read and the set of memory locations written by each executed instruction are determined by the input size and are independent of the values of the other inputs"*

```
int reduce(int n, arr[n]) {
  for(int i=0; i<n; ++i)
    sum += arr[i];
}
```

```
int findmin(int n, a[n]) {
  for(int i=1; i<n; i++)
    if(a[i]<a[0]) a[0] = a[i];
}
```

```
int finditem(list_t list)
  item = list.head;
  while(item.value!=0 && item.next!=NULL)
    item=item.next;
}
```

- **Class question: Can an algorithm decide whether a program is oblivious or not?**
  - Answer: no, proof similar to decision problem whether a program always outputs zero or not

Structural obliviousness as stronger property

*"A program is **structurally-oblivious** if any value used in a conditional branch, and any value used to compute indices or pointers is structurally-dependent only in the input variable(s) that contains the problem size but not on any other input"*

Structurally oblivious or not?

```
int reduce(int n, arr[n]) {
  for(int i=0; i<n; ++i)
    sum += arr[i];
}
```

```
int oblivious(int n, a[n], b[n]) {
  for(int i=0; i<n; ++i) {
    x = a[i] + 1;
    if (x > a[i]) b[i] = 1;
    else b[i] = 2;
} }
```

```
int finditem(list_t list)
  item = list.head;
  while(item.value!=0 && item.next!=NULL)
    item=item.next;
}
```

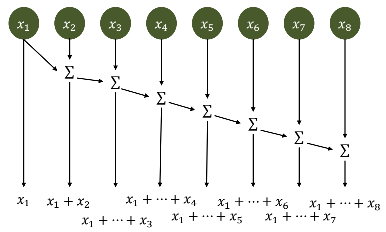
- **Clear that structurally oblivious programs are also execution oblivious**
  - Can be programmatically (statically decided)
  - Sufficient for practical use
- **The middle example is not structurally oblivious but execution oblivious**
  - First branch is always taken (assuming no overflow) but static dependency analysis is conservative

Why obliviousness?

- **We can easily reason about oblivious algorithms**
  - Execution DAG can be constructed "statically"
  - We have done this in the last weeks intuitively but you never asked how to do it for BFS for example ☺
- **Simple example (that you know): parallel summation**
  - Question: what is W(n) and D(n) of sequential summation?
    W(n)=D(n)=n-1
  - Question: is this optimal? How would you define optimality?
    Separate for W and D! Typically try to achieve both!
  - Question: what is W(n) and D(n) of the optimal parallel summation?
    W(n)=n-1 D(n)=$\lceil \log_2 n \rceil$
    Are both W and D optimal?
    Yes!

Starting simple: optimality?

- **Next example you know: scan!**
  - For a vector $[x_1, x_2, \dots, x_n]$ compute vector of n results: $[x_1; x_1 + x_2; x_1 + x_2 + x_3; \dots; x_1 + x_2 + x_i \dots + x_{n-1} + x_n]$
  - Simple serial schedule



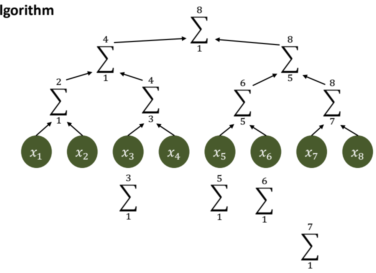
Class question: work and depth?

W(n) = n-1, D(n) = n-1

Class question: is this optimal?

What did we learn earlier?

- **Recursive to get to $W = O(n)$ and $D = O(\log n)$! Assume $n = 2^k$ for simplicity!**
  - Sounds "optimal", doesn't it? Well, let's look at the constants!
- **Algorithm**



Class question: work?
(hint: after the way up, all powers of two are done, all others require another operation each)

$W(n) = 2n - \log_2 n - 1$

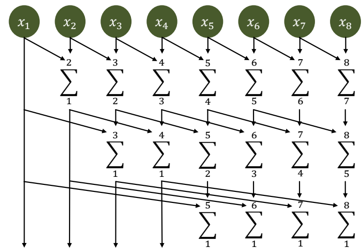
Class question: depth?
(needs to go up and down the tree)

$D(n) = 2\log_2 n - 1$

Class question: what happened to optimality?

Oh no, not good, another algorithm to the rescue!

- **Dissemination/recursive doubling – another well-known algorithmic technique – similar to trees**



Class question: work?
(hint: number of count number of omitted ops)

$W(n) = n\log_2 n - n + 1$

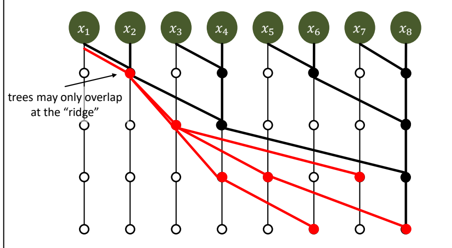
Class question: depth?

$D(n) = \log_2 n$

Class question: is this now optimal?

Oh no, three non-optimal algorithms so far!

- **Obvious question: is there a depth- and work-optimal algorithm?**
  - This took years to settle! The answer is surprisingly: no
  - We know, for parallel prefix: $W + D \geq 2n - 2$



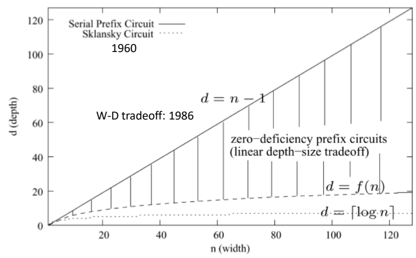
Output tree:
- leaves are all inputs, rooted at x_n
- binary due to binary operation
- $W = n - 1, D = D_o$

Input tree:
- rooted at x_1, leaves are all outputs
- not binary (simultaneous read)
- $W = n - 1$

Ridge can be at most D_o long!
Now add trees and subtract shared vertices:
$(n-1) + (n-1) - D_o = 2n - 2 - D_o \leq W$
q.e.d.

Work-Depth Tradeoffs and deficiency

"The deficiency of a prefix circuit c is defined as $\mathrm{def}(c) = W_c + D_c - (2n - 2)$*"*



Latest 2006 result for zero-deficiency construction for $n > F(D+3) - 1$ ($f(n)$ is inverse)

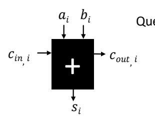
From Zhu et al.: "Construction of Zero-Deficiency Parallel Prefix Circuits"

Work- and depth-optimal constructions

- **Work-optimal?**
  - Only sequential! Why?
  - $W = n - 1$, thus $D = 2n - 2 - W = n - 1$ q.e.d. ☹
- **Depth-optimal?**
  - Ladner and Fischer propose a construction for work-efficient circuits with minimal depth
    $D = \lceil \log_2 n \rceil, W \leq 4n$
    Simple set of recursive construction rules (boring for class, check 1980's paper if needed)
    Has an unbounded fan-out! May thus not be practical ☹
- **Depth-optimal with bounded fan-out?**
  - Some constructions exist, interesting open problem
  - Nice research topic to define optimal circuits

But why do we care about this prefix sum so much?

- **It's the simplest problem to demonstrate W-D tradeoffs**
  - And it's one of the most important parallel primitives
- **Prefix summation as function composition is extremely powerful!**
  - Many seemingly sequential problems can be parallelized!
- **Simple first example: binary adder – $s = a + b$ (n-bit numbers)**
  - Starting with single-bit (full) adder for bit i



Question: what are the functions for s_i and $c_{out,i}$?

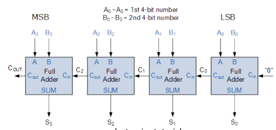
$s_i = a_i \text{ xor } b_i \text{ xor } c_{in,i}$

$c_{out,i} = a_i \text{ and } b_i \text{ or } c_{in,i} \text{ and } (a_i \text{ xor } b_i)$

Show example 4-bit addition!

Question: what is work and depth?

Example 4-bit ripple carry adder



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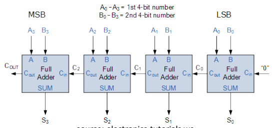
Seems very sequential, can this be parallelized?



source: electronics-tutorials.ws

- **We only want s!** $c_{out,i} = a_i \text{ and } b_i \text{ or } c_{in,i} \text{ and } (a_i \text{ xor } b_i)$
  - Requires $c_{in,1}, c_{in,2}, \dots, c_{in,n}$ though ☹ $s_i = a_i \text{ xor } b_i \text{ xor } c_{in,i}$
- **Carry bits can be computed with a scan!**
  - Model carry bit as state starting with 0
    Encode state as 1-hot vector: $q_0 = \binom{1}{0}$, $q_1 = \binom{0}{1}$
  - Each full adder updates the carry bit state according to a_i and b_i
    State update is now represented by matrix operator, depending on a_i and b_i ($M_{a_ib_i}$):
    $M_{00} = \begin{pmatrix}1 & 1\\0 & 0\end{pmatrix}$, $M_{10} = M_{01} = \begin{pmatrix}0 & 1\\1 & 0\end{pmatrix}$, $M_{11} = \begin{pmatrix}0 & 0\\1 & 1\end{pmatrix}$
  - Operator composition is defined on algebraic ring ({0, 1, or, and}) – i.e., replace "+" with "and" and "*" with "or"
    Prefix sum on the states computes now all carry bits in parallel!
- **Example: a=011, b=101 → M_{11}, M_{10}, M_{01}**
  - Scan computes: $M_{11} = \begin{pmatrix}0 & 0\\1 & 1\end{pmatrix}$; $M_{11}M_{10} = \begin{pmatrix}0 & 0\\1 & 1\end{pmatrix}$; $M_{11}M_{10}M_{01} = \begin{pmatrix}0 & 0\\1 & 1\end{pmatrix}$ in parallel
  - All carry states and s_i can now be computed in parallel by multiplying scan result with q_0

Prefix sums as magic bullet for other seemingly sequential algorithms

- **Any time a sequential chain can be modeled as function composition!**
  - Let $f_1, \dots, f_n$ be an ordered set of functions and $f_0(x) = x$
  - Define ordered function compositions: $f_1(x); f_2(f_1(x)); \dots ; f_n(\dots f_1(x))$
  - If we can write function composition $g(x) = f_i(f_{i-1}(x)$ as $g = f_i \circ f_{i-1}$ then we can compute $\circ$ with a prefix sum!
    We saw an example with the adder (M_{ab} were our functions)
- **Example: linear recurrence $f_i(x) = a_i f_{i-1}(x) + b_i$ with $f_0(x)$=x**
  - Write as matrix form $f_i\binom{x}{1} = \begin{pmatrix}a_i & b_i\\0 & 1\end{pmatrix} f_{i-1}\binom{x}{1}$
  - Function composition is now simple matrix multiplication!
    For example: $f_2\binom{x}{1} = \begin{pmatrix}a_2 & b_2\\0 & 1\end{pmatrix}\begin{pmatrix}a_1 & b_1\\0 & 1\end{pmatrix} f_0\binom{x}{1} = \begin{pmatrix}a_1a_2 & a_2b_1 + b_2\\0 & 1\end{pmatrix}\binom{x}{1}$
- **Most powerful! Homework:**
  - Parallelize tridiagonal solve
  - Parallelize string parsing

Another use for prefix sums: Parallel radix sort

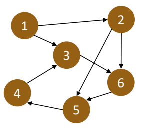
- **Radix sort works bit-by-bit**
  - Sorts k-bit numbers in k iterations
  - In each iteration i stably sort all values by the i-th bit
  - Example, k=1:
    Iteration 0: 101 111 010 011 110 001
    Iteration 1: 010 110 101 111 011 001
    Iteration 2: 101 001 010 110 111 011
    Iteration 3: 001 010 011 101 110 111
- **Now on n processors**
  - Each processor owns single k-bit number, each iteration
    low = prefix_scan(!bit, sum)
    high = n-1-backwards_prefix_scan(bit, sum)
    new_idx = (bit == 0) : low ? high
    b[new_idx] = a[i]
    swap(a,b)

Show one example iteration!

Question: work and depth?

Oblivious graph algorithms

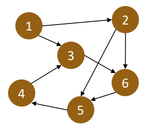
- **Seems paradoxical but isn't (may just not be most efficient)**
  - Use adjacency matrix representation of graph – "compute with all zeros"



i →, j ↓

0	1	1	0	0	0
0	0	0	0	1	1
0	0	0	0	0	1
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0	1	0

Unweighted graph – binary matrix



i →, j ↓

0	2	3	0	0	0
0	0	0	0	3	1
0	0	0	0	0	2
0	0	4	0	0	0
0	0	0	7	0	0
0	0	0	0	8	0

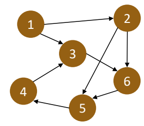
Weighted graph – general matrix

Algebraic semirings

- **A semiring is an algebraic structure that**
  - Has two binary operations called "addition" and "multiplication"
  - Addition must be associative ((a+b)+c = a+(b+c)) and commutative ((a+b=b+a)) and have an identity element
  - Multiplication must be associative and have an identity element
  - Multiplication distributes over addition (a*(b+c) = a*b+a*c) and multiplication by additive identity annihilates
  - Semirings are denoted by tuples (S, +, *, 0, 1)
    *"Standard" ring of rational numbers: (ℝ, +, *, 0, 1)*
    Boolean semiring: ({0,1}, ∨, ∧, 0, 1)
    Tropical semiring: (ℝ ∪ {∞}, min, +, ∞, 0) (also called min-plus semiring)

Oblivious shortest path search

- **Construct distance matrix from adjacency matrix by replacing all off-diagonal zeros with ∞**
- **Initialize distance vector d_0 of size n to ∞ everywhere but zero at start vertex**
  - E.g., $\mathbf{d_0} = (\infty, \mathbf{0}, \infty, \infty, \infty, \infty)^T$
    Show evolution when multiplied!
- **SSSP can be performed with n+1 matrix-vector multiplications!**
  - Question: total work and depth?
    $W = O(n^3)$, $D = O(n \log n)$
  - Question: Is this good? Optimal?
    Dijkstra = $O(|E| + |V|\log|V|)$ ☹
- **Homework:**
  - Define a similar APSP algorithm with
    $W = O(n^3 \log n)$, $D = O(\log^2 n)$



0	2	3	∞	∞	∞
∞	0	∞	∞	3	1
∞	∞	0	∞	∞	2
∞	∞	4	0	∞	∞
∞	∞	∞	7	0	∞
∞	∞	∞	∞	8	0

Oblivious connected components

- **Question: How could we compute the transitive closure of a graph?**
  - Multiply the matrix $(A + I)$ n times with itself in the Boolean semiring!
  - Why?
    Demonstrate that $(A + I)^2$ has 1s for each path of at most length 1
    By induction show that $(A + I)^k$ has 1s for each path of at most length k

- **What is work and depth of transitive closure?**
  - Repeated squaring! $W = O(n^3 \log n)$ $D = O(\log^2 n)$

- **How to get to connected components from a transitive closure matrix?**
  - Each component needs unique label
  - Create label matrix $L_{ij} = j$ iff $(A_I)^n{}_{ij} = 1$ and $L_{ij} = \infty$ otherwise
  - For each row (vertex) perform min-reduction to determine its component label!
  - Overall work and depth?
    $W = O(n^3 \log n)$, $D = O(\log^2 n)$

i →, j ↓

0	1	1	0	0	0
0	0	0	0	1	1
0	0	0	0	0	1
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0	1	0

+I

1	1	1	0	0	0
0	1	0	0	1	1
0	0	1	0	0	1
0	0	1	1	0	0
0	0	0	1	1	0
0	0	0	0	1	1

Many if not all graph problems have oblivious or tensor variants!

- **Not clear whether they are most efficient**
  - Efforts such as GraphBLAS exploit existing BLAS implementations and techniques

- **Generalizations to other algorithms possible**
  - Can everything be modeled as tensor computations on the right ring?
  - E. Solomonik, TH: *"Sparse Tensor Algebra as a Parallel Programming Model"*
  - Much of machine learning/deep learning is oblivious

- **Many algorithms get non-oblivious though**
  - All sparse algorithms are data-dependent!
  - E.g., use sparse graphs for graph algorithms on semirings (if $|E| < |V|^2/\log|V|$)
    May recover some of the lost efficiency by computing zeros!

- **Now moving to non-oblivious ☺**