Design of Parallel and High-Performance Computing

Fall 2015

Lecture: Lock-Free and distributed memory

Motivational video: *https://www.youtube.com/watch?v=PuCx50FdSic*

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Administrivia

- **Final presentations: Monday 12/14 (two weeks!)**
  - Should have (pretty much) final results
  - Show us how great your project is
  - Some more ideas what to talk about:

    Which architecture(s) did you test on?

    How did you verify correctness of the parallelization?

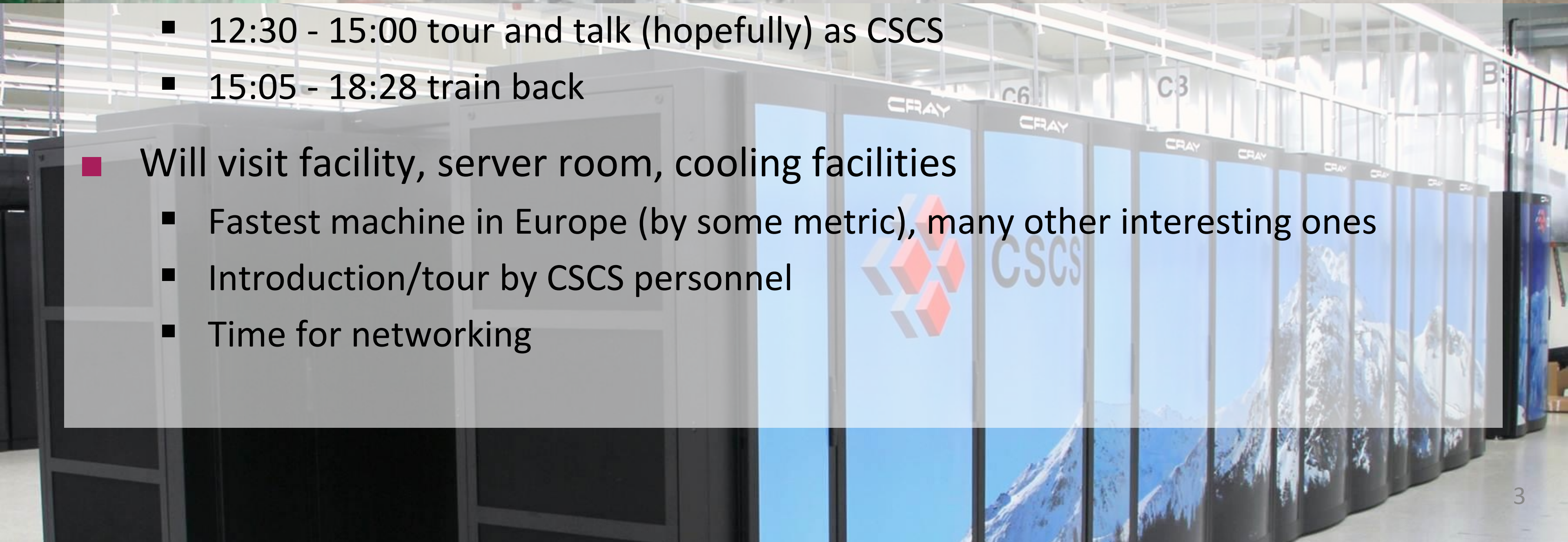
    Use bounds models for comparisons!

    (Somewhat) realistic use-cases and input sets?

    Emphasize on the key concepts (may relate to theory of lecture)!

    What are remaining issues/limitations?
- **Report will be due in January!**
  - Still, starting to write early is very helpful --- write – rewrite – rewrite (no joke!)
  - Last unit today: Entertainment with bogus results!

DPHPC Excursion



- **Will be after exam ☺**
  - Week of February 15

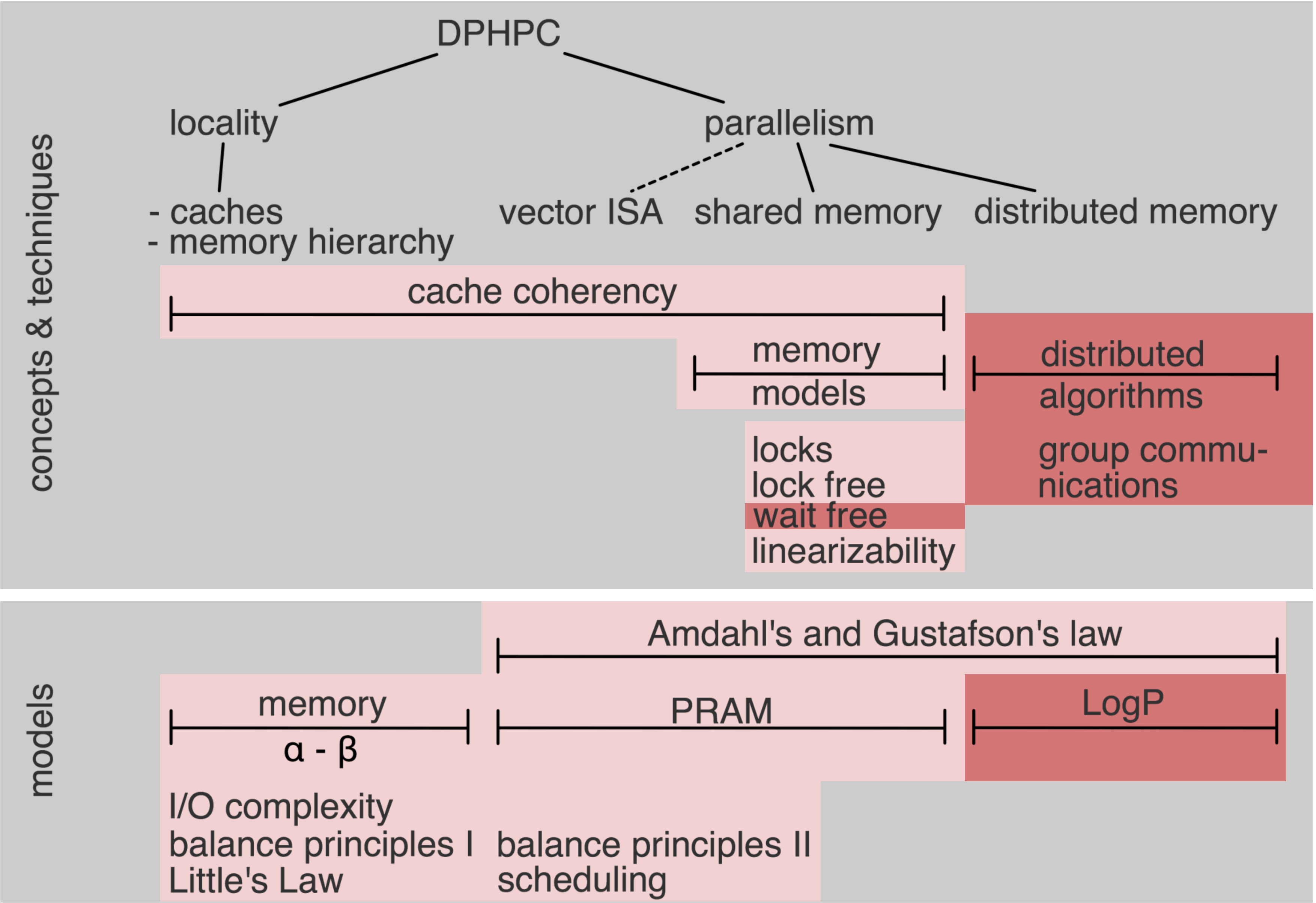
    (last week before semester, which starts February 22)
- Proposed schedule (may change on request):
  - 9:00 meet at HB
  - 9:09 train leaves, arrives at 12:08 at CSCS (transfer by bus)

    Possibly light pizza lunch (TBA)
  - 12:30 - 15:00 tour and talk (hopefully) as CSCS
  - 15:05 - 18:28 train back
- Will visit facility, server room, cooling facilities
  - Fastest machine in Europe (by some metric), many other interesting ones
  - Introduction/tour by CSCS personnel
  - Time for networking

Review of last lecture

- **MCS – do not forget ☺**
  - RW locks
  - Lock properties/issues (deadlock, priority inversion, blocking vs. spinning)
  - Competitive spinning
- **Locked and Lock-free tricks**
  - (coarse-grained locking)
  - Fine-grained locking
  - RW locking
  - Optimistic synchronization
  - Lazy locking
  - Lock-free (& wait-free)
- **Finish wait-free/lock-free**
  - Consensus hierarchy

DPHPC Overview



Goals of this lecture

- **Scheduling (was 1st unit)**

- **Finish wait-free/lock-free**
  - Consensus hierarchy
  - The promised proof!

- **Scientific benchmarking!**
  - Common mistakes!
  - How to improve current practice
  - Important for your project

    Brush up your statistics

Lock-free and wait-free

- **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

    valid: 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

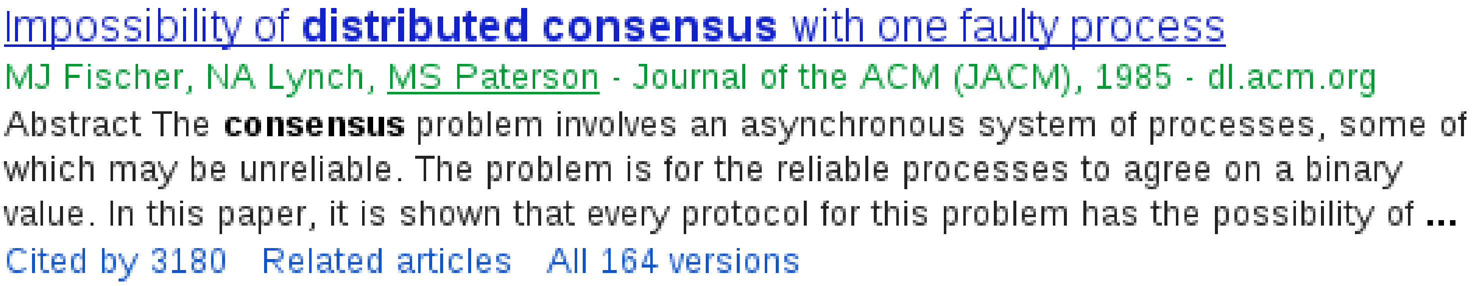
    Example with two threads and two moves each!

Atomic Registers

- **Theorem [Herlihy'91]: Atomic registers have consensus number one**
  - 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 TM!
- **Proof technique borrowed from:**



Impossibility of **distributed consensus** with one faulty process

MJ Fischer, NA Lynch, MS Paterson - Journal of the ACM (JACM), 1985 - dl.acm.org

Abstract The **consensus** problem involves an asynchronous system of processes, some of which may be unreliable. The problem is for the reliable processes to agree on a binary value. In this paper, it is shown that every protocol for this problem has the possibility of **...**

Cited by 3180 Related articles All 164 versions

- **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!

Compare and Set/Swap Consensus

```
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
}
```

- **CAS provides an infinite consensus number**
  - 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 ☺

- **Not really … ;-)**
  - We'll argue about **performance** now!
- **But you have all the tools for:**
  - Efficient locks
  - Efficient lock-based algorithms
  - Efficient lock-free algorithms (or even wait-free)
  - Reasoning about parallelism!
- **What now?**
  - A different class of problems

    Impact on wait-free/lock-free on actual performance is not well understood
  - Relevant to HPC, applies to shared and distributed memory

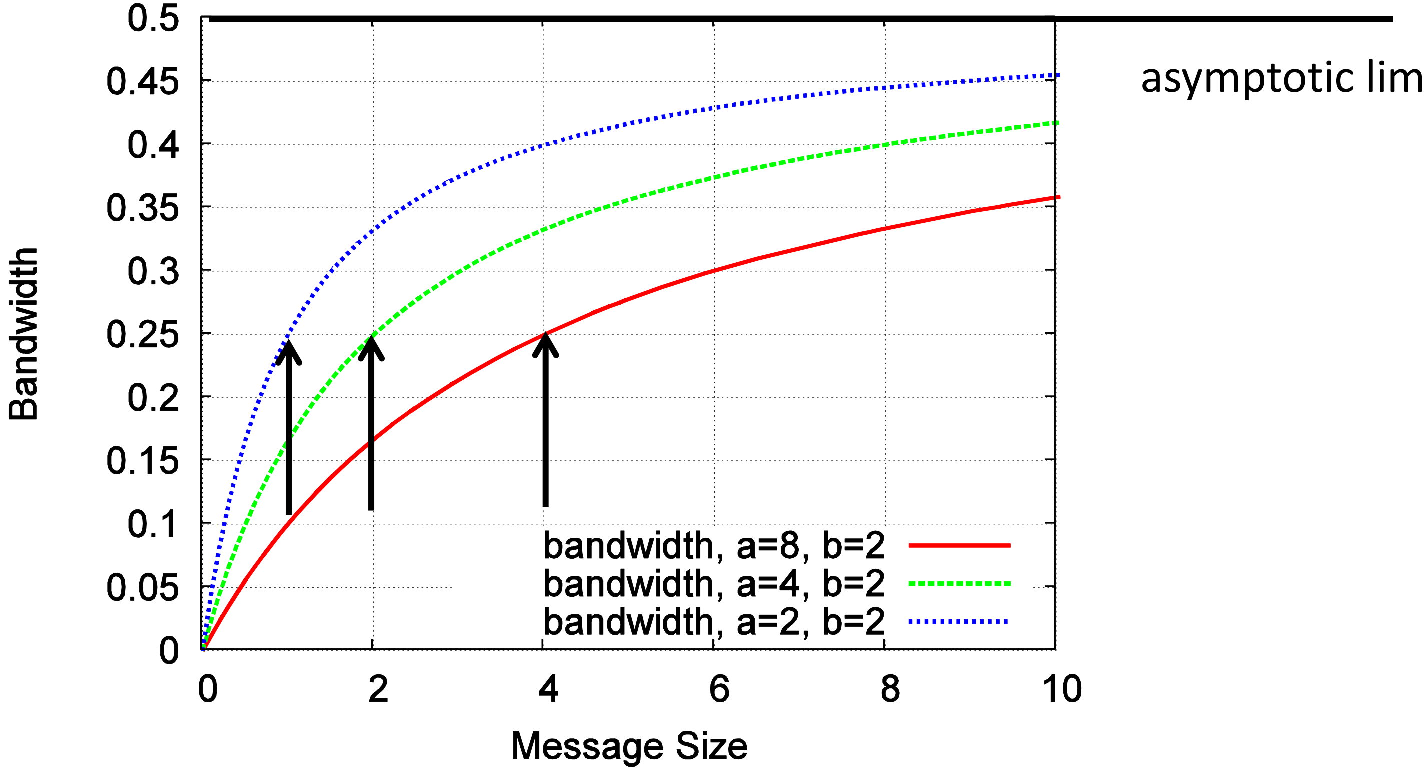
    → *Group communications*

Remember: A Simple Model for Communication

- **Transfer time $T(s) = \alpha+\beta s$**
  - α = startup time (latency)
  - β = cost per byte (bandwidth=$1/\beta$)
- **As s increases, bandwidth approaches $1/\beta$ asymptotically**
  - Convergence rate depends on α
  - $s_{1/2} = \alpha/\beta$
- **Assuming no pipelining (new messages can only be issued from a process after all arrived)**

Bandwidth vs. Latency

- **$s_{1/2} = \alpha/\beta$ often used to distinguish bandwidth- and latency-bound messages**
  - $s_{1/2}$ is in the order of kilobytes on real systems



asymptotic limit

Quick Example

- **Simplest linear broadcast**
  - One process has a data item to be distributed to all processes
- **Broadcasting s bytes among P processes:**
  - $T(s) = (P-1) * (\alpha+\beta s) = \mathcal{O}(P)$
- **Class question: Do you know a faster method to accomplish the same?**

k-ary Tree Broadcast

- **Origin process is the root of the tree, passes messages to k neighbors which pass them on**
  - k=2 -> binary tree
- **Class Question: What is the broadcast time in the simple latency/bandwidth model?**
  - $T(s) \approx \lceil log_k(P) \rceil \cdot k \cdot (\alpha + \beta \cdot s) = \mathcal{O}(log(P))$ (for fixed k)
- **Class Question: What is the optimal k?**
  - $0 = \frac{ln(P) \cdot k}{ln(k)} \frac{d}{dk} = \frac{ln(P) ln(k) - ln(P)}{ln^2(k)} \rightarrow k = e = 2.71...$
  - Independent of P, α, βs? Really?

Faster Trees?

- **Class Question: Can we broadcast faster than in a ternary tree?**
  - Yes because each respective root is idle after sending three messages!
  - Those roots could keep sending!
  - Result is a k-nomial tree

    For k=2, it's a binomial tree

- **Class Question: What about the runtime?**
  - $T(s) = \lceil log_k(P) \rceil \cdot (k-1) \cdot (\alpha + \beta \cdot s) = \mathcal{O}(log(P))$
- **Class Question: What is the optimal k here?**
  - T(s) d/dk is monotonically increasing for k>1, thus k_{opt}=2
- **Class Question: Can we broadcast faster than in a k-nomial tree?**
  - $\mathcal{O}(log(P))$ is asymptotically optimal for s=1!
  - But what about large s?

Open Problems

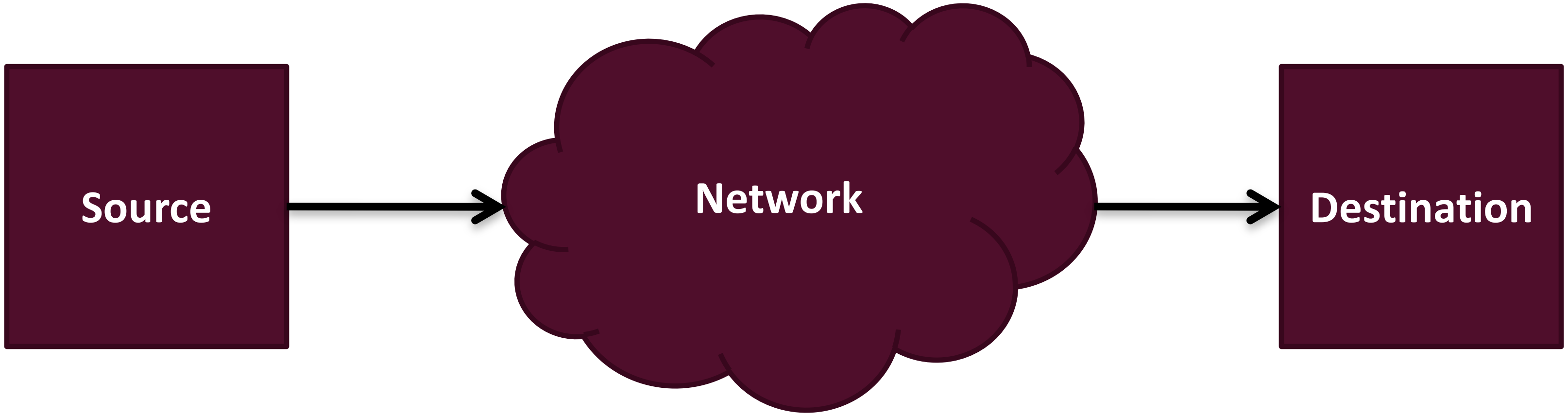
- **Look for optimal parallel algorithms (even in simple models!)**
  - And then check the more realistic models
  - Useful optimization targets are MPI collective operations

    Broadcast/Reduce, Scatter/Gather, Alltoall, Allreduce, Allgather, Scan/Exscan, …
  - Implementations of those (check current MPI libraries ☺)
  - Useful also in scientific computations

    Barnes Hut, linear algebra, FFT, …
- **Lots of work to do!**
  - Contact me for thesis ideas (or check SPCL) if you like this topic
  - Usually involve optimization (ILP/LP) and clever algorithms (algebra) combined with practical experiments on large-scale machines (10,000+ processors)

HPC Networking Basics

- **Familiar (non-HPC) network: Internet TCP/IP**
  - Common model:

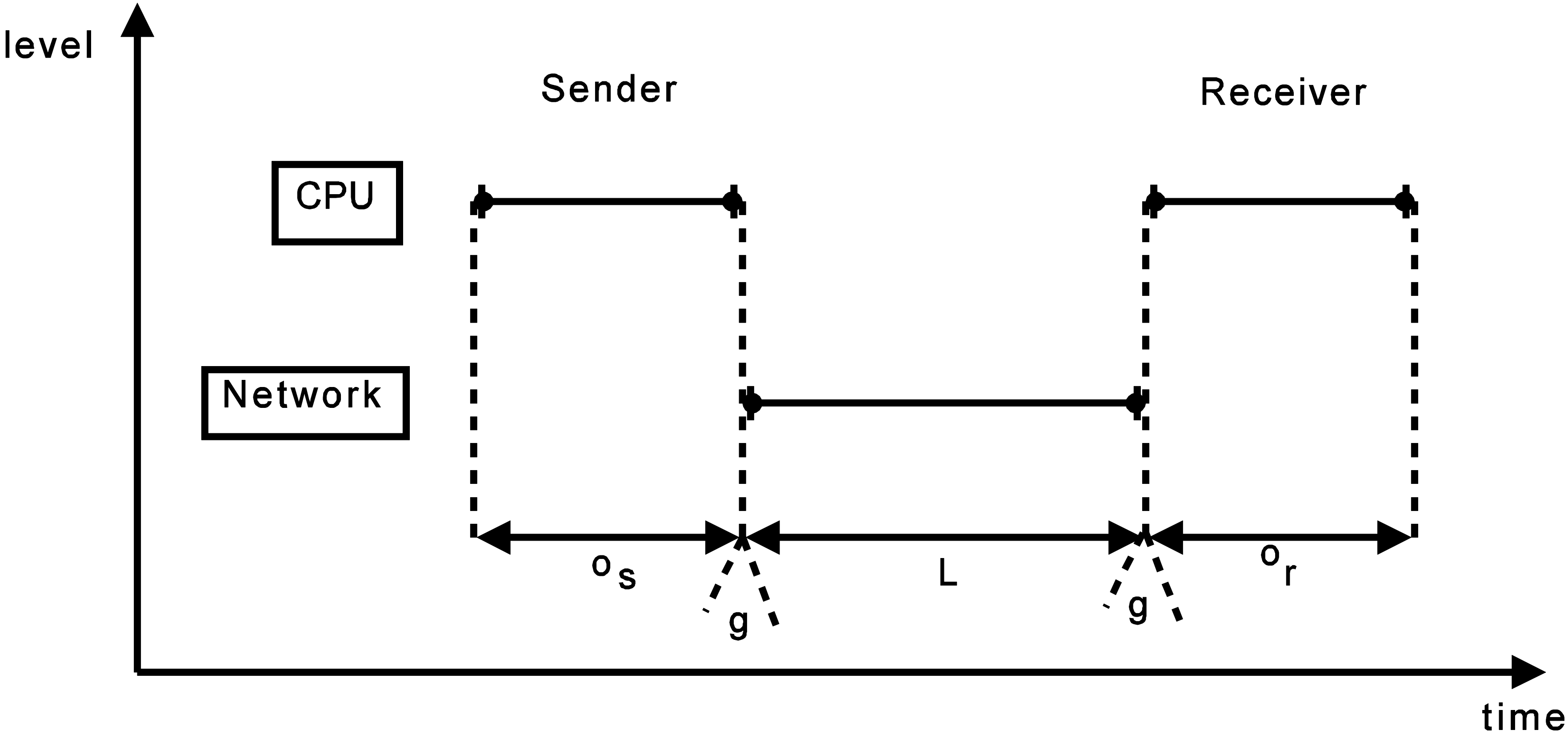


- **Class Question: What parameters are needed to model the performance (including pipelining)?**
  - Latency, Bandwidth, Injection Rate, Host Overhead

The LogP Model

- **Defined by four parameters:**
  - L: an upper bound on the latency, or delay, incurred in communicating a message containing a word (or small number of words) from its source module to its target module.
  - o: the overhead, defined as the length of time that a processor is engaged in the transmission or reception of each message; during this time, the processor cannot perform other operations.
  - g: the gap, defined as the minimum time interval between consecutive message transmissions or consecutive message receptions at a processor. The reciprocal of g corresponds to the available per-processor communication bandwidth.
  - P: the number of processor/memory modules. We assume unit time for local operations and call it a cycle.

The LogP Model



Simple Examples

- **Sending a single message**
    - $T = 2o+L$
- **Ping-Pong Round-Trip**
    - $T_{RTT} = 4o+2L$
- **Transmitting n messages**
    - $T(n) = L+(n-1)*\max(g, o) + 2o$

Simplifications

- **o is bigger than g on some machines**
  - g can be ignored (eliminates max() terms)
  - be careful with multicore!
- **Offloading networks might have very low o**
  - Can be ignored (not yet but hopefully soon)
- **L might be ignored for long message streams**
  - If they are pipelined
- **Account g also for the first message**
  - Eliminates “-1”

Benefits over Latency/Bandwidth Model

- **Models pipelining**
  - L/g messages can be “in flight”
  - Captures state of the art (cf. TCP windows)
- **Models computation/communication overlap**
  - Asynchronous algorithms
- **Models endpoint congestion/overload**
  - Benefits balanced algorithms

Example: Broadcasts

- **Class Question: What is the LogP running time for a linear broadcast of a single packet?**
  - $T_{lin} = L + (P-2) * \max(o,g) + 2o$
- **Class Question: Approximate the LogP runtime for a binary-tree broadcast of a single packet?**
  - $T_{bin} \leq \log_2 P * (L + \max(o,g) + 2o)$
- **Class Question: Approximate the LogP runtime for an k-ary-tree broadcast of a single packet?**
  - $T_{k\text{-}n} \leq \log_k P * (L + (k-1)\max(o,g) + 2o)$

Example: Broadcasts

- **Class Question: Approximate the LogP runtime for a binomial tree broadcast of a single packet (assume L > g!)?**
  - $T_{bin} \leq \log_2 P * (L + 2o)$
- **Class Question: Approximate the LogP runtime for a k-nomial tree broadcast of a single packet?**
  - $T_{k\text{-}n} \leq \log_k P * (L + (k-2)\max(o,g) + 2o)$
- **Class Question: What is the optimal k (assume o>g)?**
  - Derive by k: $0 = o * \ln(k_{opt}) - L/k_{opt} + o$ (solve numerically)

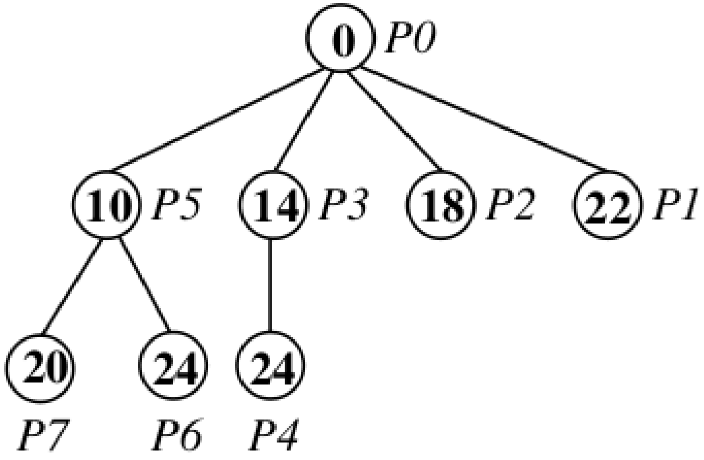
    For larger L, k grows and for larger o, k shrinks
  - Models pipelining capability better than simple model!

Example: Broadcasts

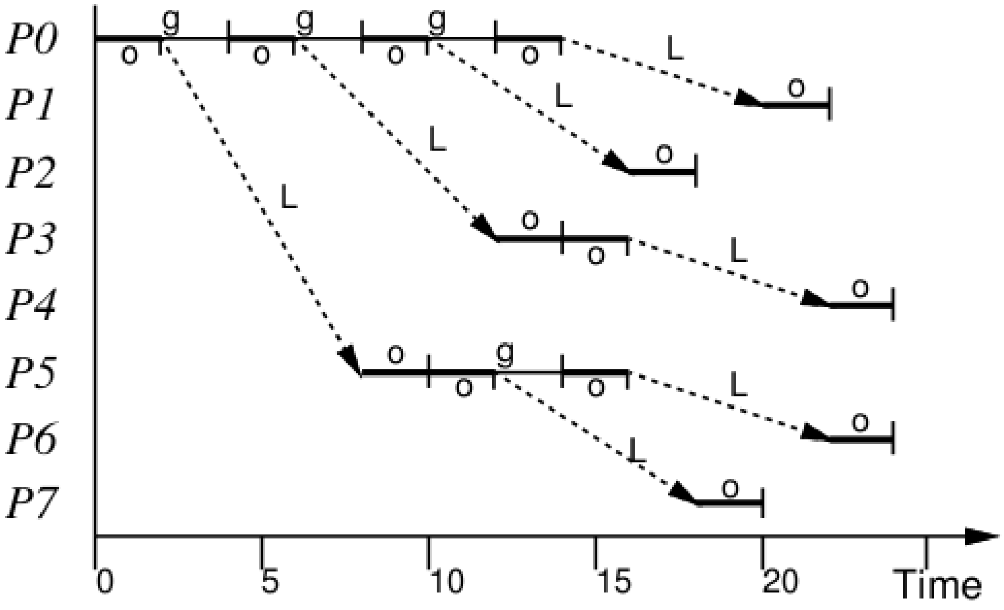
- **Class Question: Can we do better than k_{opt}-ary binomial broadcast?**
  - Problem: fixed k in all stages might not be optimal
  - We can construct a schedule for the optimal broadcast in practical settings
  - First proposed by Karp et al. in “Optimal Broadcast and Summation in the LogP Model”

Example: Optimal Broadcast

- **Broadcast to P-1 processes**
  - Each process who received the value sends it on; each process receives exactly once



P=8, L=6, g=4, o=2



Optimal Broadcast Runtime

- **This determines the maximum number of PEs (P(t)) that can be reached in time t**
- **P(t) can be computed with a generalized Fibonacci recurrence (assuming o>g):**

$$P(t) = \begin{cases} 1 : & t < 2o + L \\ P(t-o) + P(t-L-2o) : & \text{otherwise.} \end{cases} \qquad (1)$$

- **Which can be bounded by (see [1]):** $2^{\left\lfloor \frac{t}{L+2o} \right\rfloor} \leq P(t) \leq 2^{\left\lfloor \frac{t}{o} \right\rfloor}$
  - A closed solution is an interesting open problem!

[1]: Hoefler et al.: “Scalable Communication Protocols for Dynamic Sparse Data Exchange” (Lemma 1)

The Bigger Picture

- **We learned how to program shared memory systems**
  - Coherency & memory models & linearizability
  - Locks as examples for reasoning about correctness and performance
  - List-based sets as examples for lock-free and wait-free algorithms
  - Consensus number
- **We learned about general performance properties and parallelism**
  - Amdahl’s and Gustafson’s laws
  - Little’s law, Work-span, …
  - Balance principles & scheduling
- **We learned how to perform model-based optimizations**
  - Distributed memory broadcast example with two models
- **What next? MPI? OpenMP? UPC?**
  - Next-generation machines “merge” shared and distributed memory concepts → Partitioned Global Address Space (PGAS)