BLUE WATERS

SUSTAINED PETASCALE COMPUTING

Toward Performance Models of MPI Implementations for Understanding Application Scaling Issues

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Imagine …

- … you're planning to construct a multi-million Dollar Supercomputer …
- … that consumes as much energy as a small [european] town …
- … to solve computational problems at an international scale and advance science to the next level …
- … with "hero-runs" of [insert verb here] scientific applications that cost $10k and more per run …

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… and all you have (now) is …

- … then you better plan ahead! (same for Exascale)

Application Performance Modeling

- Analytic expression for expected runtime
  - Often exists as *folklore* in people's minds
- Can estimate scalability of codes and algorithms
  - Folklore: Alltoall(v) is not scalable
- Helps to make design decisions
  - E.g., estimate trade-off between single-core performance and scalability
    - General principle: reduce communication with more/redundant computation

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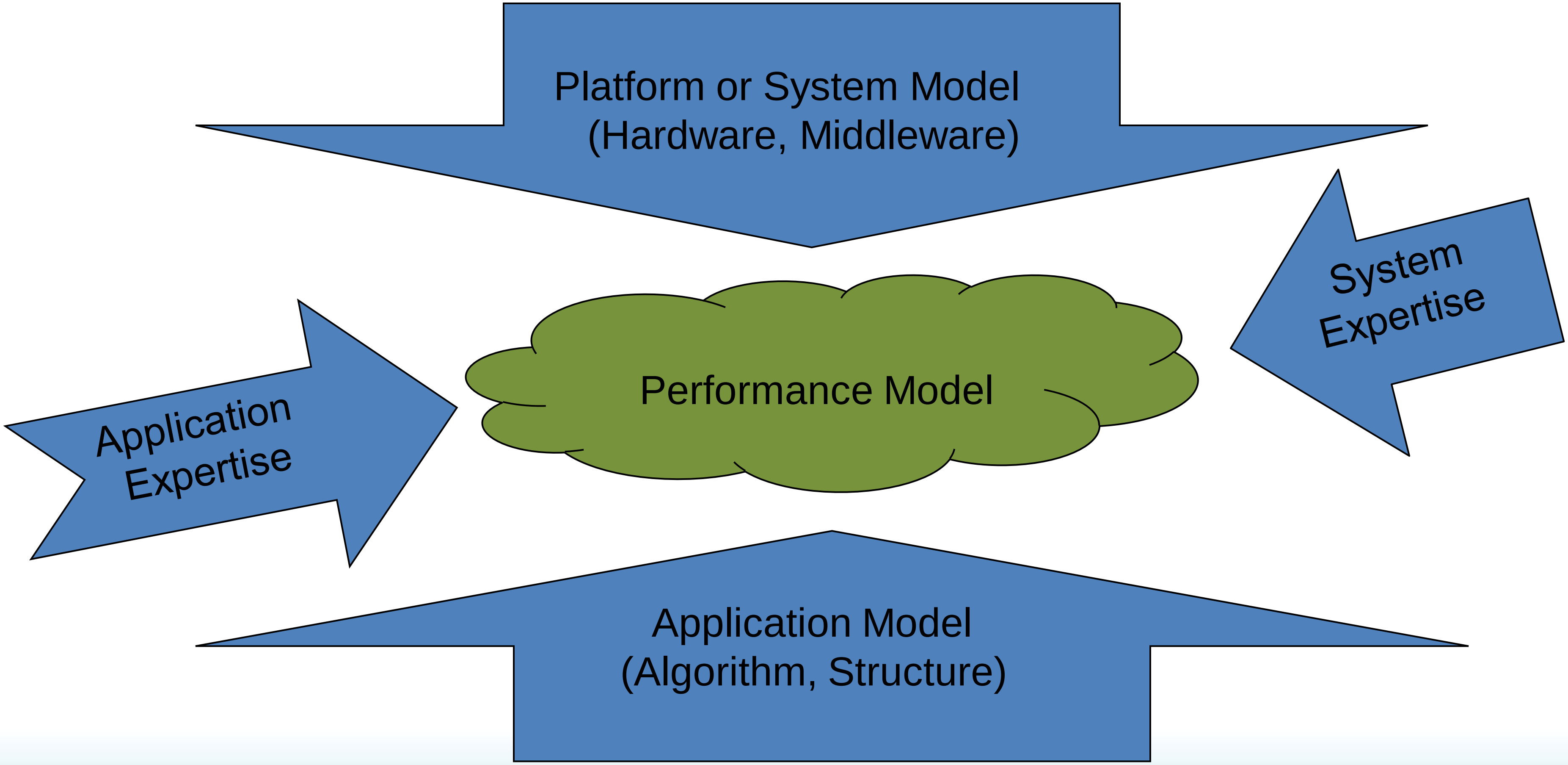
Performance Modeling from 10.000 Feet



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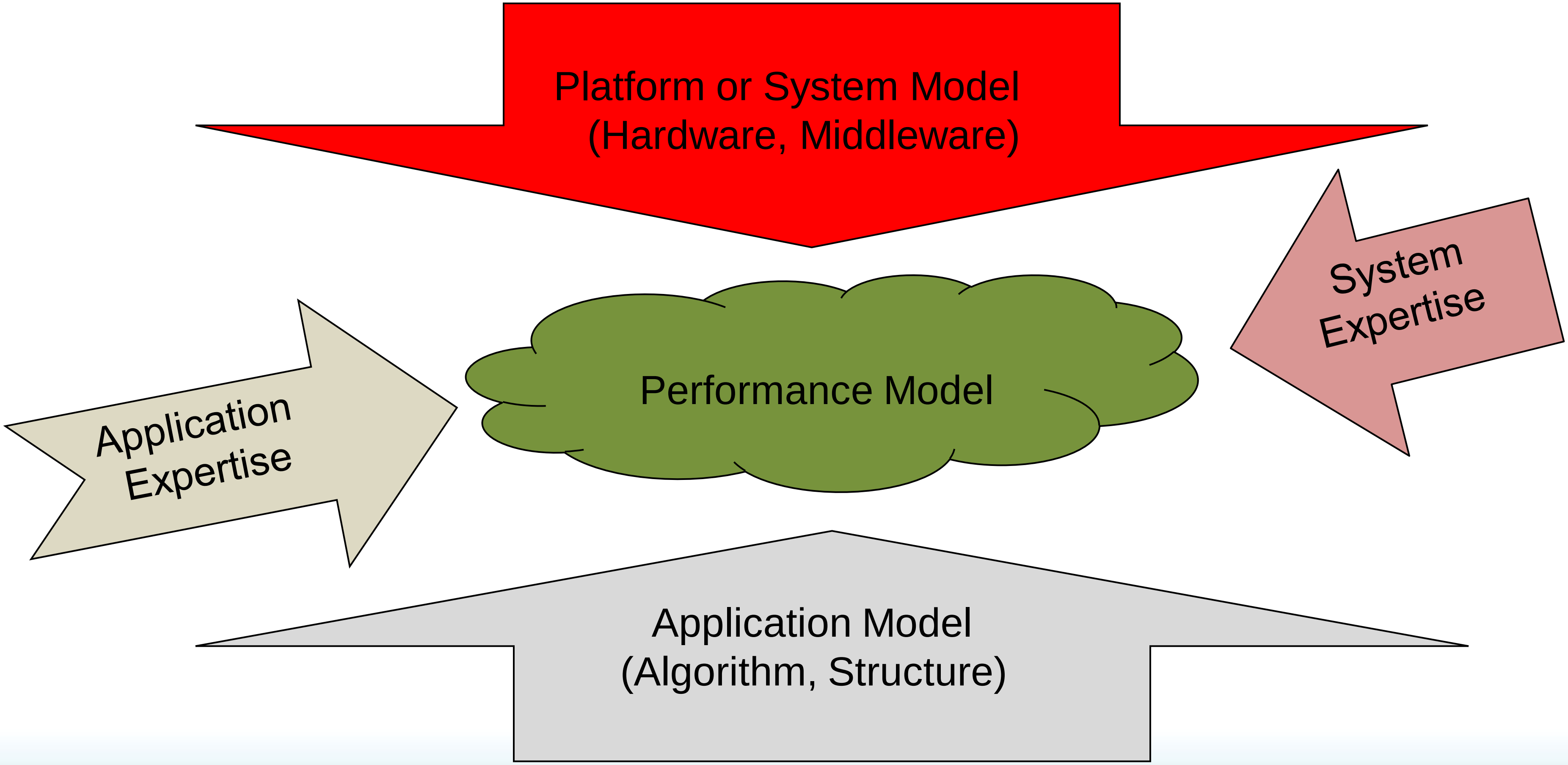
MPI is part of the Platform Model



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MPI Performance Models are Critical

- Folklore exists, e.g.,
  - Transmitting a message of size S = $\Theta(S)$
  - MPI_Alltoall on P processes = $\mathcal{O}(P)$
- Model inaccuracies often insignificant for small S,P!
  - Huge impact for large S, P
- E.g., application models assume MPI_Bcast or MPI_Allreduce = $\Theta(S \log(P)) \rightarrow$ wrong
  - A good implementation = $\Theta(S + \log(P))$

An Approach to Standardized Models

- Giving accurate estimates is a hard task
  - Users might see it as a contract
  - Vendors are hesitant to agree to or define contracts
- Many variables
  - CPU parameters (memory, speed, architecture, …)
  - Network parameters (latency, bw, topology, …)
  - Protocols (eager, rendezvous, …)
- We propose hierarchical modeling
  - Various levels of accuracy

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The Four Levels of Accuracy

1. **Asymptotic**
   - Asymptotic scaling only, e.g., $\Theta(S + \log(P))$
2. **Dominant term exact**
   - Significant terms, e.g., $\beta S + \mathcal{O}(\log(P)) < 2\beta S + \mathcal{O}(\log(P))$
3. **Bounded (parameterized)**
   - Specify bounds, e.g., $\beta S + \log(P) < T < 2\beta S + \log(P)$
4. **Exact**
   - Exact model (if possible), e.g., $T_{BAR} = 0.95\mu s$

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Current Point-to-Point Models

- Asymptotic (trivial): $\Theta(S)$
- Latency-bandwidth models: $T = \alpha + S\beta$
- Need to consider different protocol ranges
- Exact model for BG/P:

$$T(S) = \begin{cases} 4.5\mu s + 2.67ns/B \cdot S: & S \leq 256B \\ 5.7\mu s + 2.67ns/B \cdot S: & 256B < S \leq 1024B \\ 9.8\mu s + 2.67ns/B \cdot S: & 1024B < S \end{cases}$$

- Used Netgauge/logp benchmark
- Three ranges: small, eager, rendezvous

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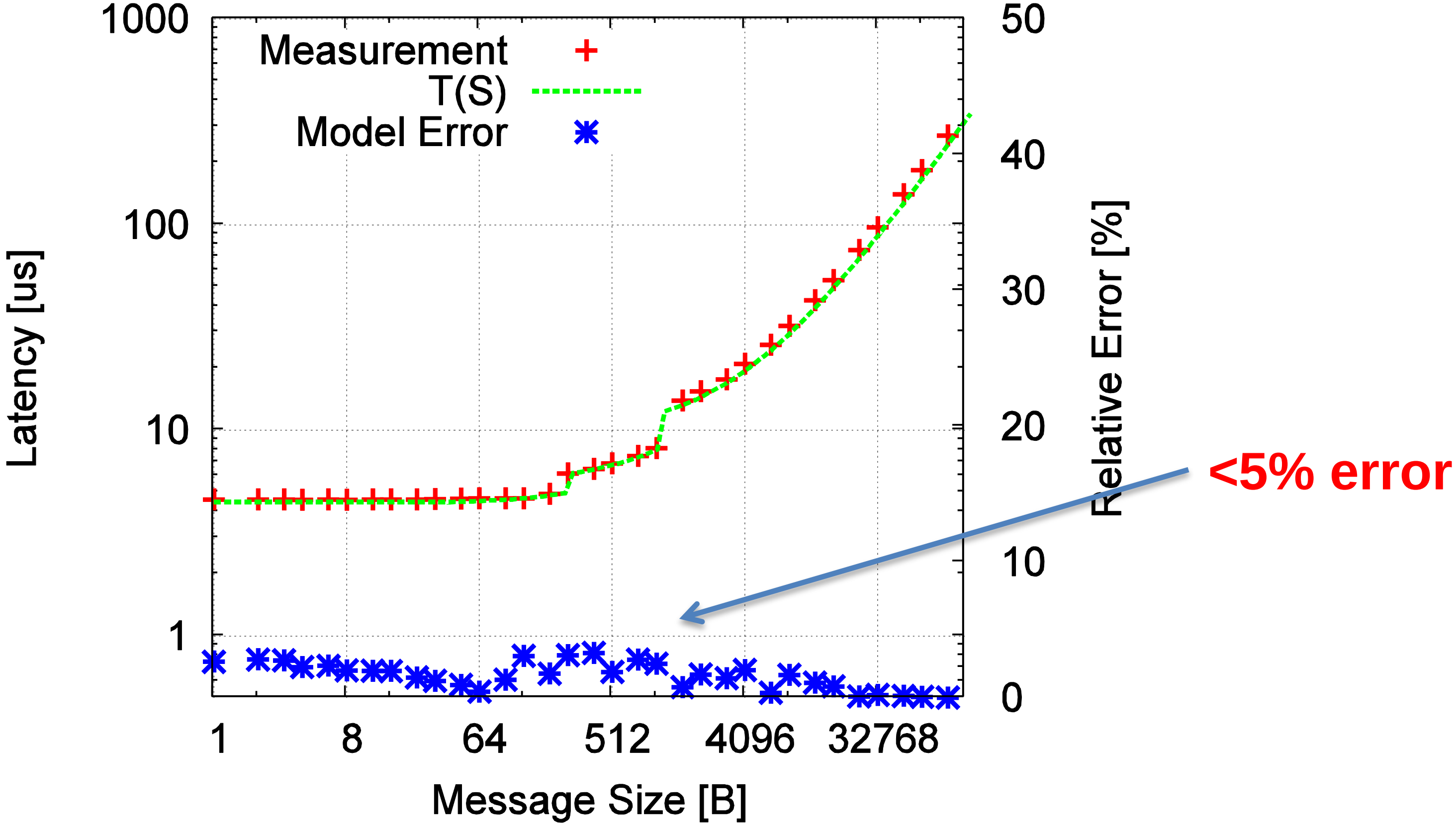
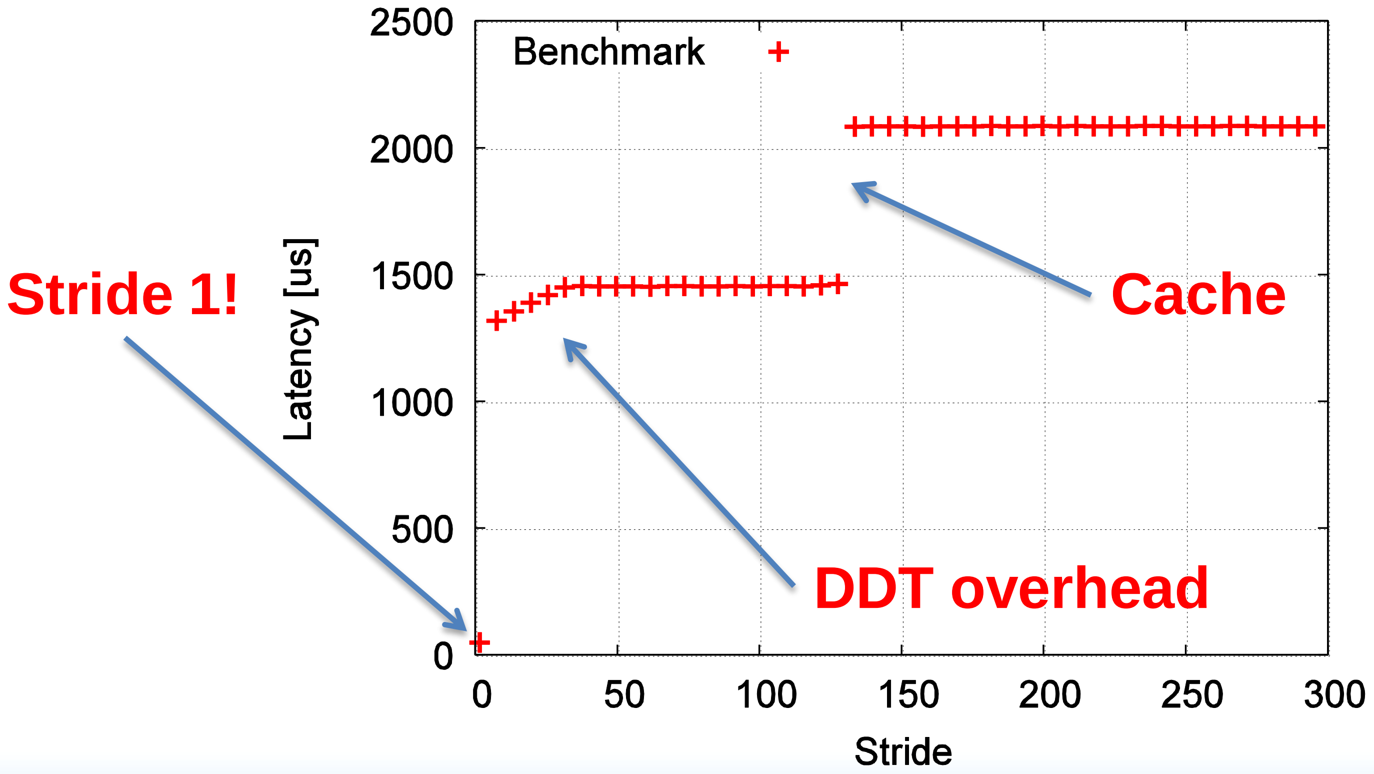
Model Accuracy



- Looks good, but there are problems!

The not-so-ideal (but realistic) Case I

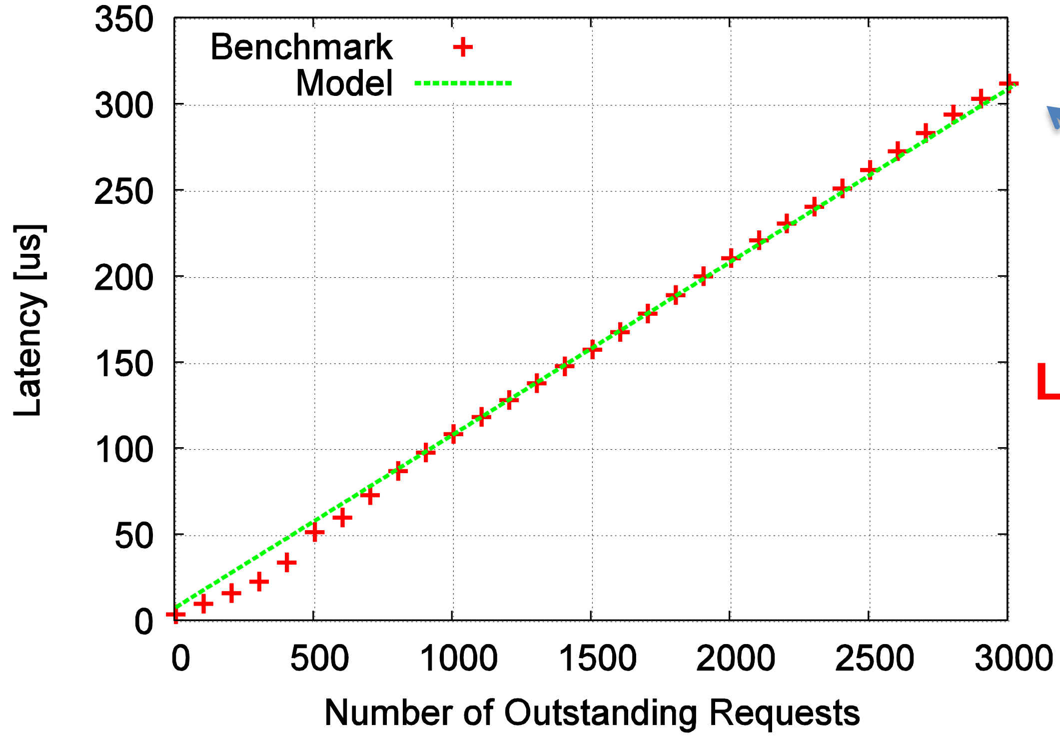
- Strided data-access (model assumed stride-1)



- Benchmark: Netgauge: one_one_dtype

The not-so-ideal (but realistic) Case II

- Matching queue overheads (very common)



Latency factor of 35!

- R requests: $T_{match}(R) \leq 100ns \cdot R; \;\; T(13) \leq 1.3\mu s$
  - Benchmark: Netgauge/one_one_req_queue

The not-so-ideal (but realistic) Case III

- Congestion is often ignored
  - Very hard to determine but worst-case can be calculated
  - effective Bisection Bandwidth
    - Average bandwidth of a random perfect matching
- Upper bound is congestion-less (see model)
- Lower bound assumes worst-case mapping
  - Assume ideal adaptive routing (BG/P)
  - Congestion of $\mathcal{O}(\sqrt[3]{P})$ per link

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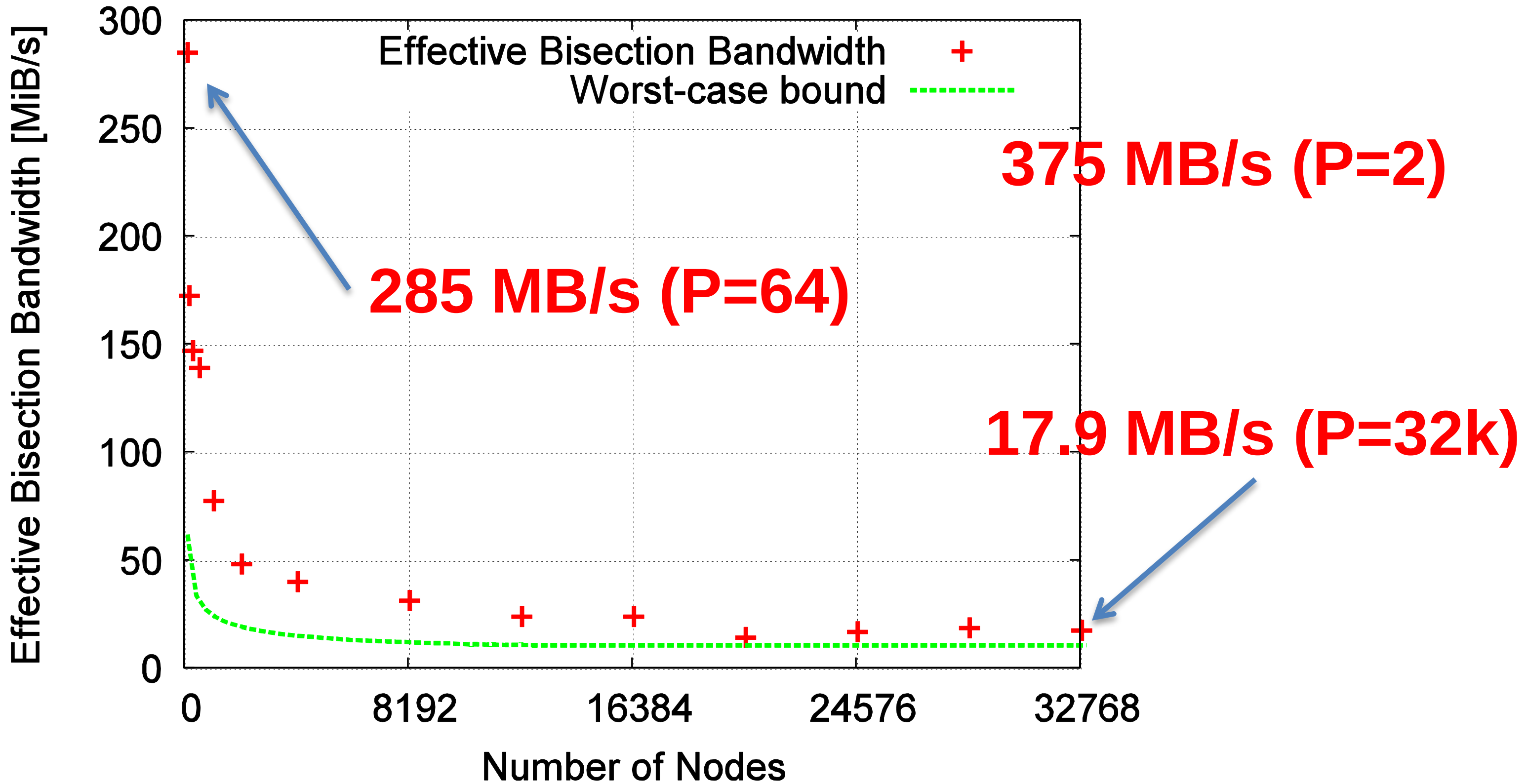
Worst-case vs. Average Case Congestion



- Average seems to converge to worst-case (large P)
  - Benchmark: Netgauge/ebb

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Bounded Model with Congestion

$$9.8\mu s + 2.67^{ns}/_{B} \cdot S \leq T(S,P) < 9.8\mu s + 2.67^{ns}/_{B} \cdot S \cdot {}^{3}/_{2}\sqrt[3]{P}$$

- Only considers congestion
  - Needs to add datatypes, matching queue, …
- Some parameters might be ignored
  - Typically application-specific
  - E.g., application only uses stride-1 access

Collective Communication

- Crucial for estimating application scalability
- Often simpler to use than p2p models
  - Matching queue, synchronization and cong. hidden
- Simple latency-bandwidth: $T = \alpha(P) + S \cdot \beta(P)$
  - Empirical parameterization, might be hard to use
- Build upon point-to-point models
  - E.g., LogGOPS model
  - More complex to derive (and often less precise)

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Example: Small MPI_Bcast, MPI_Allreduce

- Handled by Collective (Tree) network in BG/P
- MPI_Bcast: $T_{BC}(P,8) = \alpha_T + \beta_T^{BC} \log_2(P)$
  - α_T = startup overhead
  - β_T = cost per stage
  - Empirically determined: $\alpha_T = 13\mu s,\ \beta_T^{BC} = 0.31\mu s$
- MPI_Allreduce: $T_{ARE}(P,8) = \alpha_T^{SUM} + \beta_T^{SUM} \log_2(P)$
  - Empirically determined: $\beta_T^{SUM} = 0.37\mu s$

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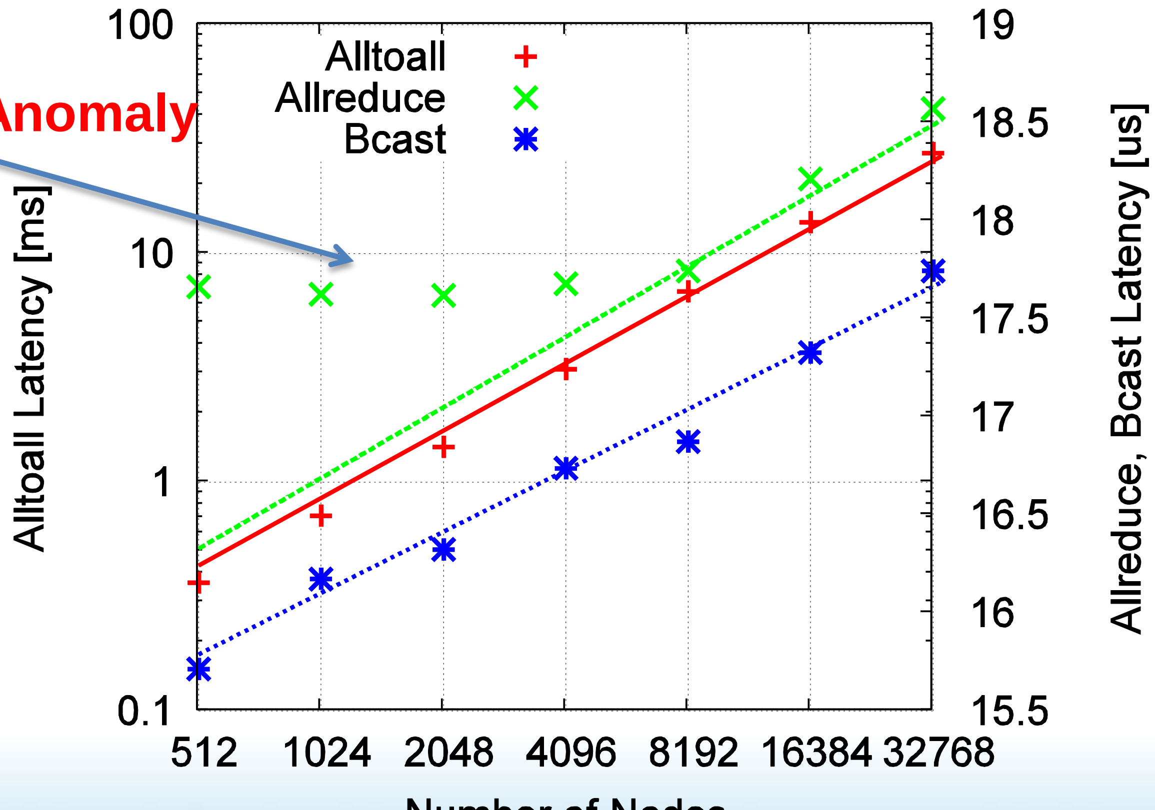
Small MPI_Alltoall

- Direct sends (**not** optimal!): $T_{A2A}(P,8) = \alpha + g(P-1)$

Performance Anomaly



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Large MPI_Bcast

- Exact model for small MPI_Bcast
- Large bcast needs $T_{BC}(P,8)$ to reach all processes
  - Extend with bandwidth term
- Assume using all six torus links (2.67ns/B/link)
  - $T_{BC}(P,S) = \alpha_T + \beta_T^{BC}\log_2(P) + \frac{2.67}{6}ns/B \cdot S$
- Based on first-principles (documentation+LogGP)
  - No fit necessary
  - Still accurate for large S (see next slides)
    - Middle-ground can be covered by less accurate models

Large MPI_Alltoall

- Algorithm sends to all targets (random permutation)
  - Uses all six links, hits bisection bandwidth
  - Model: $T_{A2A} = (P-1)g + SG \cdot \max\{\frac{P-1}{6}, C(P)\}$
- Simple counting argument for C(P)
  - Assume k^3 processor grid, 1-d distance $d = \frac{k-1}{2}$
  - Total number of occupied links:

$$N(k) \leq k^3 \cdot 2\sum_{x=0}^{d} 2\sum_{y=0}^{d} 2\sum_{z=0}^{d}(x+y+z) = k^3 12d\,(d+1)^3 = \mathcal{O}(k^7)$$

  - Total number of links: $6k^3$
  - Congestion per link: $C(P) \leq \sqrt[3]{P}(\sqrt[3]{P}/2+1)^3 = \mathcal{O}(P\sqrt[3]{P})$
    - Model: $T_{A2A} \geq g(P-1) + SG\sqrt[3]{P}(\sqrt[3]{P}/2+1)^3$

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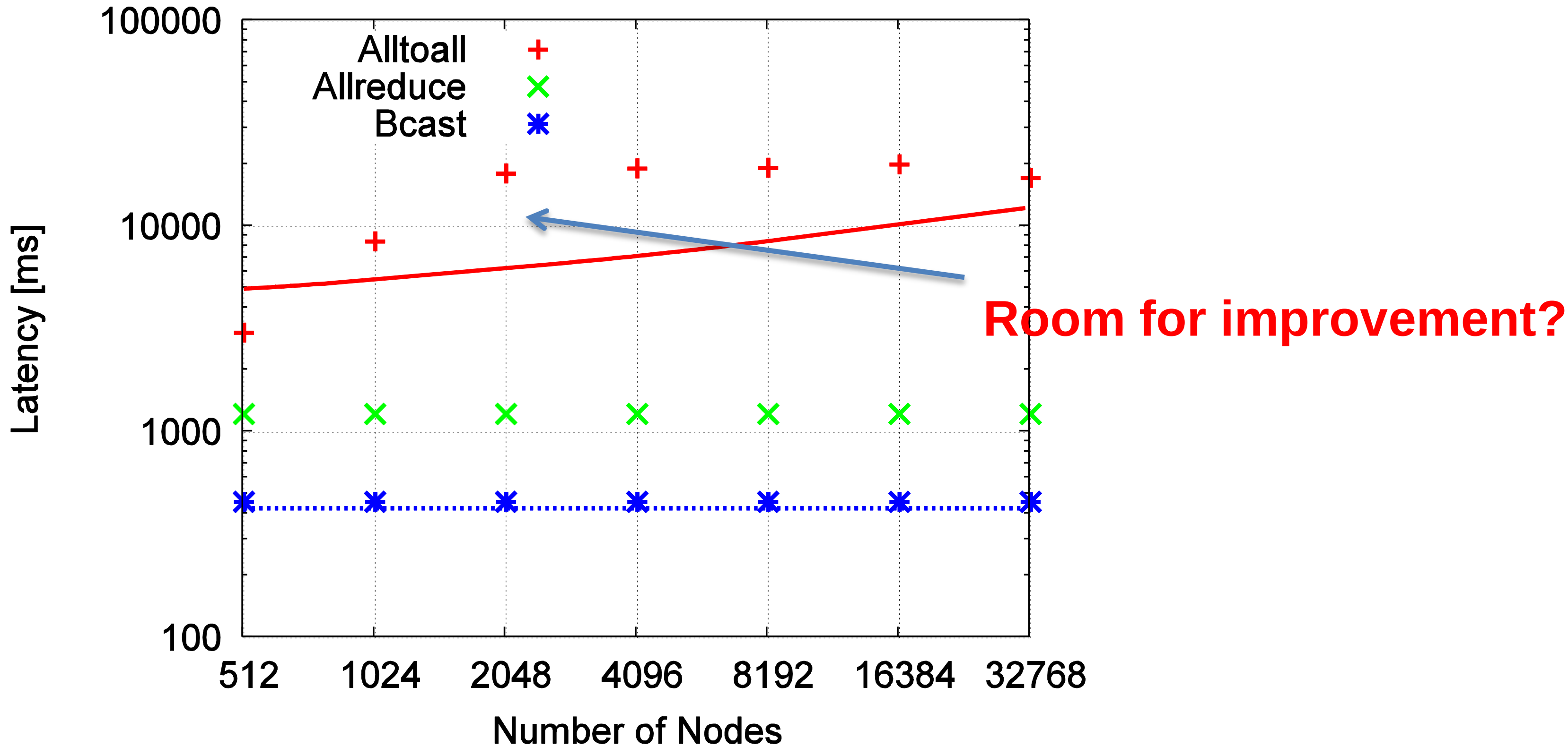
Results for Large Collectives



- No model for MPI_Allreduce (constant)
- Lower-bound for MPI_Alltoall holds

Takeaways, Questions & Discussion

- MPI Libraries should provide performance models!
  - Different levels allow accuracy/effort trade-off
    - Even black-box models work
  - Models greatly benefit application design
  - Models are useful to check performance consistency
  - Reasoning about large-scale
    - Is the current MPI performance sufficient?
  - Model design is a community effort!
    - More research needed!