ETH
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Swiss Federal Institute of Technology Zurich

Application-Centric Benchmarking and Modeling for Co-Design

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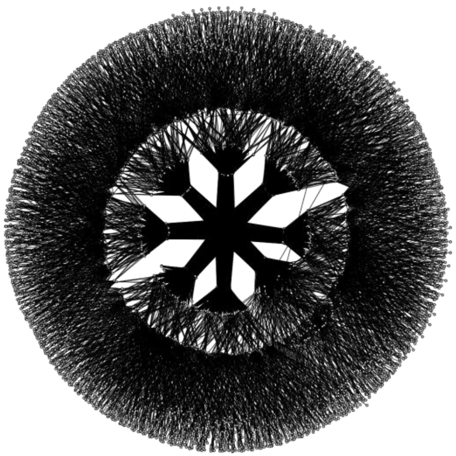
Exascale Applications and Software Conference

Edinburgh, Scotland, UK

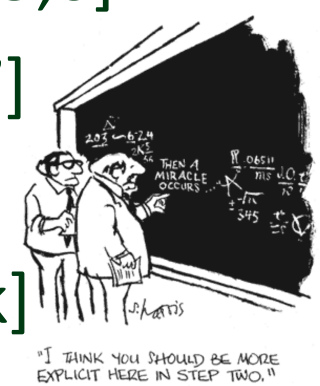
Why Modeling and Co-Design?

- Number of PEs grows exponentially
- Bottlenecks shift quickly
  - e.g., to data serialization
- Some aspects are over-engineered
  - At least for the “average application”
- How do we know what applications need?
  - At scale?



Performance Modeling

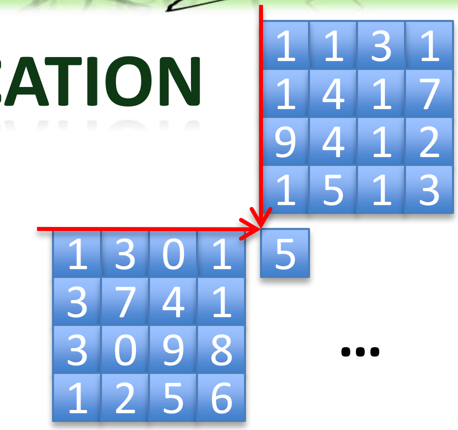
- Allows to:
  1. Predict performance at a different scale [1,2]
  2. Predict performance on a different machine [3,4]
  3. Predict performance for a different problem [5,6]
  4. Assess impact of network topology choices [7]
  5. Find performance bugs [to appear]
  6. Determine application requirements [this talk]



[1]: Zhai et al.:"Phantom: predicting performance of parallel applications on large-scale […]", PPoPP'10
[2]: Lee et al.: "Methods of inference and learning for performance modeling of parallel applications.", PPoPP'07
[3]: Marin, Mellor-Crummey: "Cross-architecture performance predictions for scientific applications […]", SIGMETRICS'04
[4]: Yang et al.: "Cross-platform performance prediction of parallel applications using partial execution.", SC'05
[5]: Hoefler et al.: "Performance modeling for systematic performance tuning", SC'11
[6]: Kerbyson et al.: "Predictive performance and scalability modeling of a large-scale application.", SC'01
[7]: Bauer et al.: "Performance Modeling and Comparative Analysis of the MILC Lattice QCD Application su3 rmd", CCGrid'12

Simplest Example – Matrix Multiplication

```
for(int i=0; i<N; ++i)
  for(int j=0; j<N; ++j)
    for(int k=0; k<N; ++k)
      C[i+j*N] += A[i+k*N] * B[k+j*N];
```

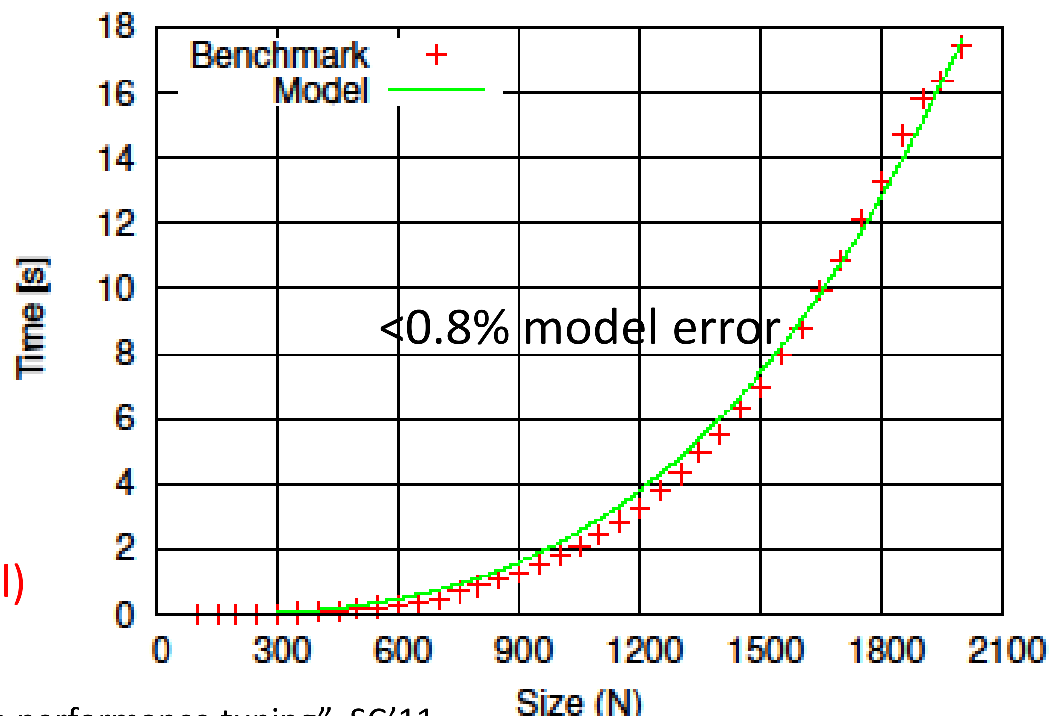


- Semi-Analytic Perf. Modeling [1]:

Algorithmic (analytic) Parameters

- T(N) = tN^3
  - t=2.2ns

Architectural (empirical) Parameters

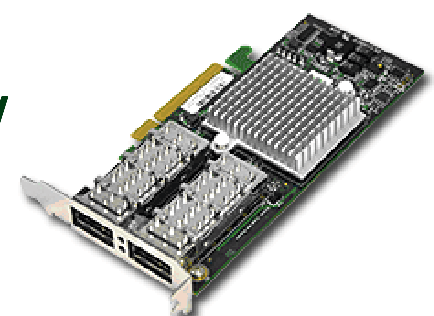


[1]: Hoefler et al.: "Performance modeling for systematic performance tuning", SC'11

Requirements Modeling

- Dual to performance modeling
  - What we **get** vs. what we **need**!
- Allows to model requirements of applications
  - E.g., FLOPs, Memory Bandwidth, …
  - Rules of thumb: "1 Byte/Word per FLOP"
  - Better: "balance principles" [1]

- Burton's interpretation of Little's law
  - concurrency = latency x bandwidth

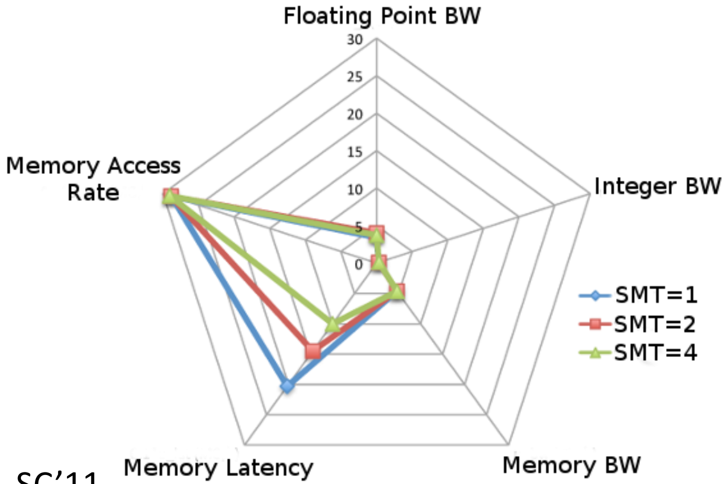


minimum needed — to hide latency — and keep system busy

[1]: Czechowski et al: "Balance Principles for Algorithm-Architecture Co-design", HotPar'11

Model Requirements

- System features
  - Memory/Network Latency, Bandwidth, Flops, …
- Requirements space of system X
  - Feature vector F defines limits
  - Each application run has a requirement vector R
  - In general R < F
  - Bottlenecks are easily identified



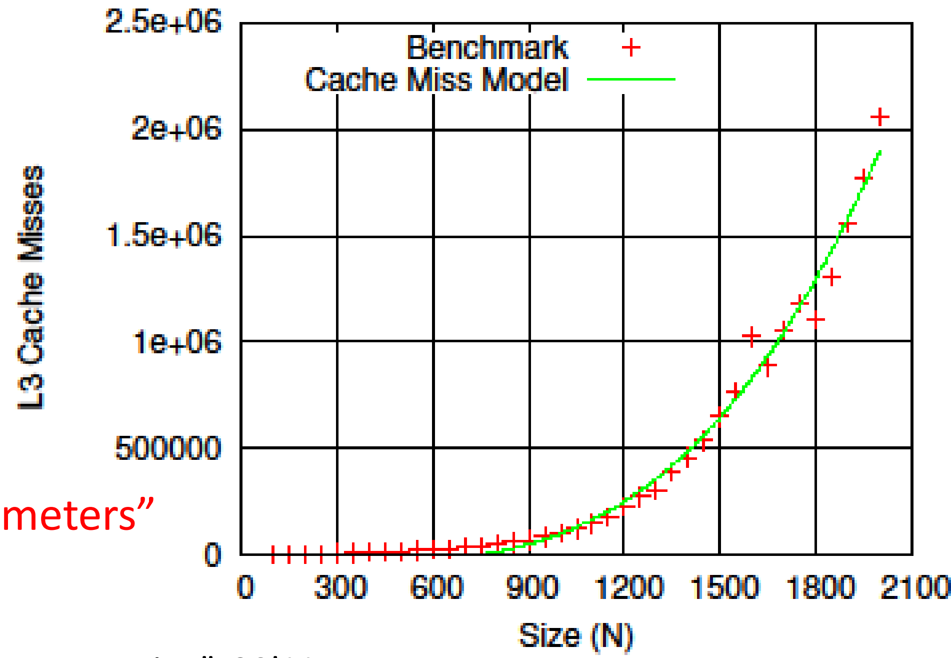
[1]: Hoefler et al.: "Performance modeling for systematic performance tuning", SC'11

Parametric Requirements Model

- Requirements vectors are not enough
  - Back to our simple example: Matrix Multiplication!
    - $2N^3$ FLOP/s
    - Memory bandwidth?
- LLC Misses:
  - $C(N) = aN^3 - bN^2$
  - a=3.8e-4
  - b=2.7e-1

"Algorithmic Parameters"

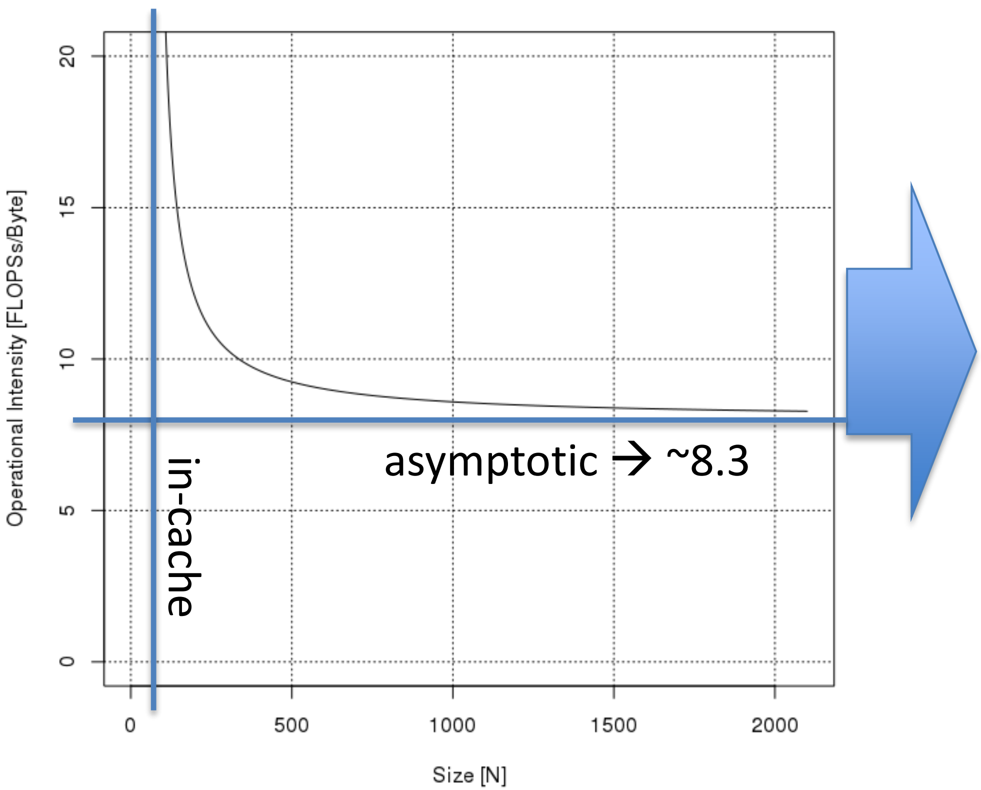
"Architectural Parameters"



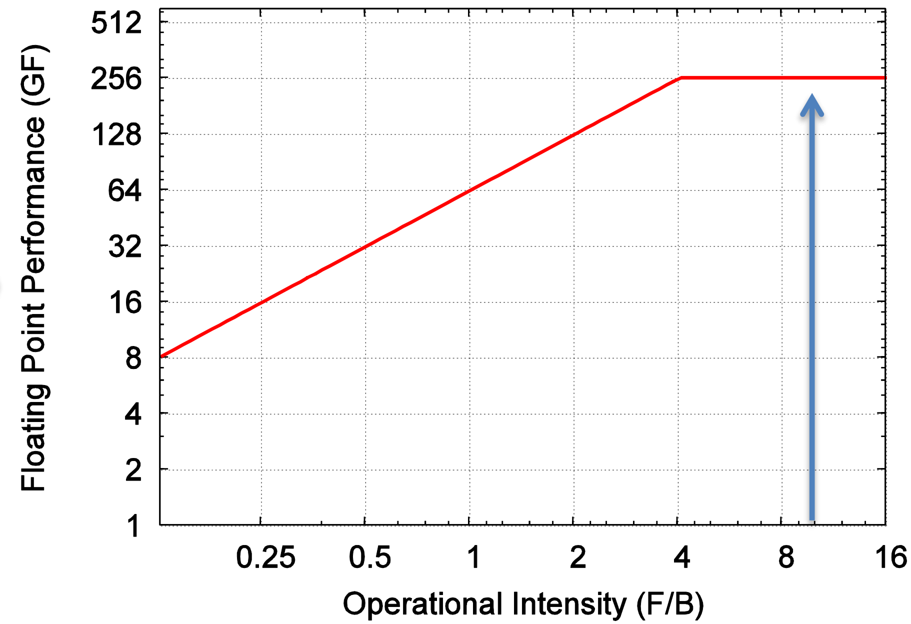
[1]: Hoefler et al.: "Performance modeling for systematic performance tuning", SC'11

How is the Balance?

Operational Intensity



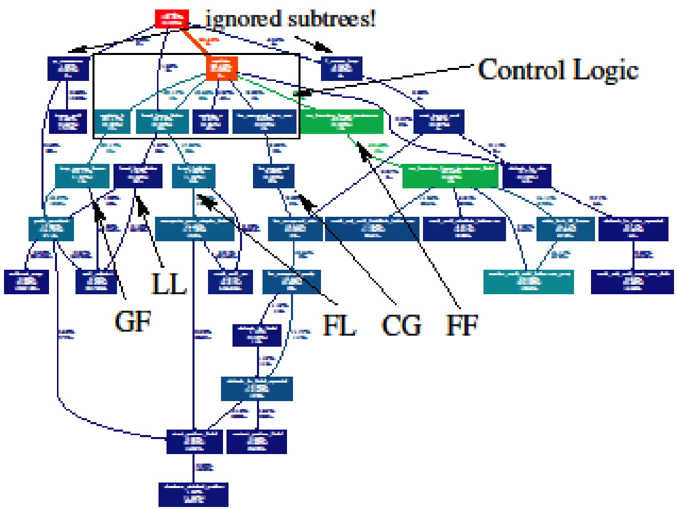
Roofline Visualization

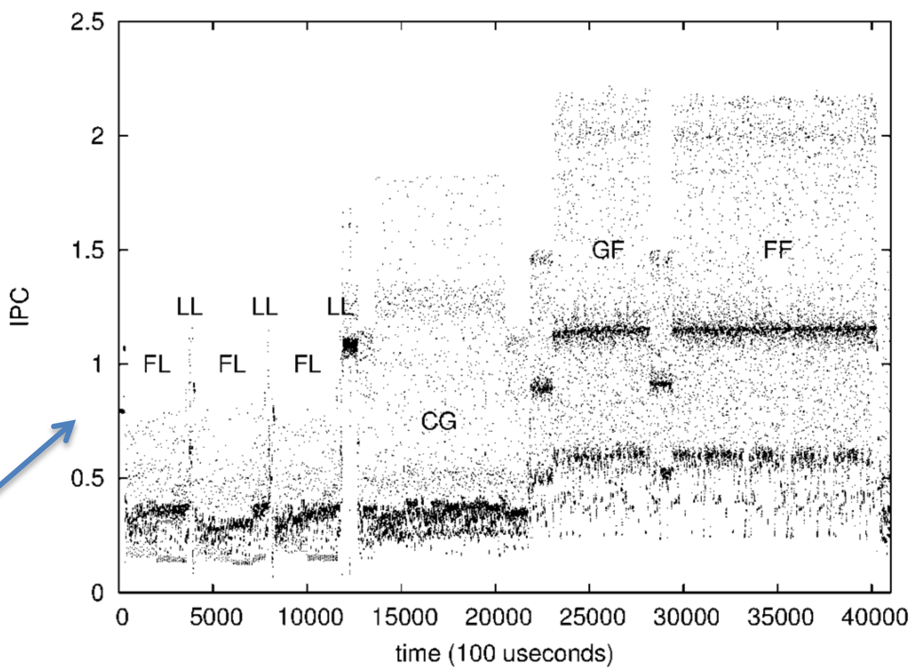


- MM needs < ½ memory bandwidth
  - Small problems even less

A REAL (SIMPLE) APPLICATION

- MILC – MIMD Lattice Computation, su3_rmd
- Well understood and modeled [1]
  - Five phases: FL, LL, CG, GF, FF

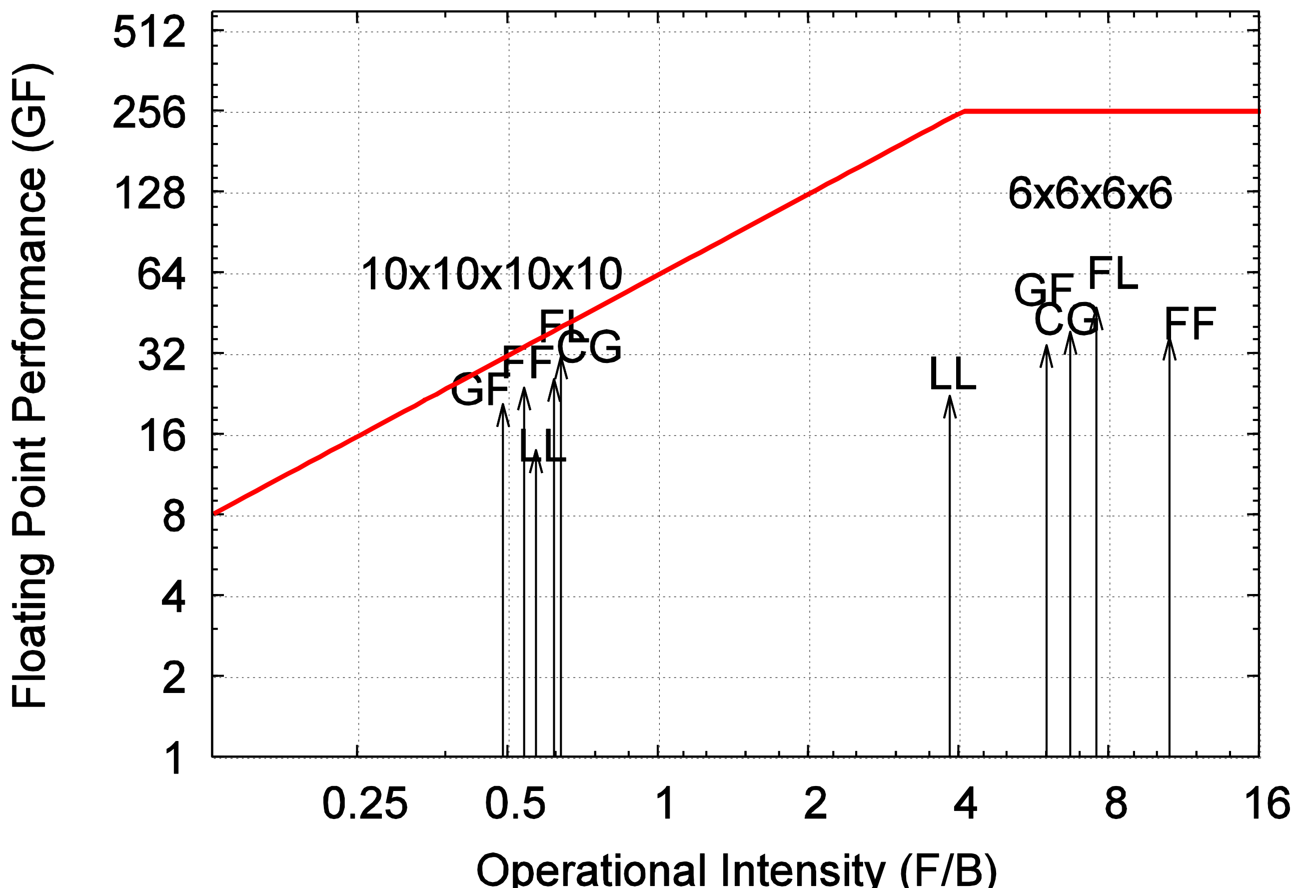




  - Phase detection can be automated

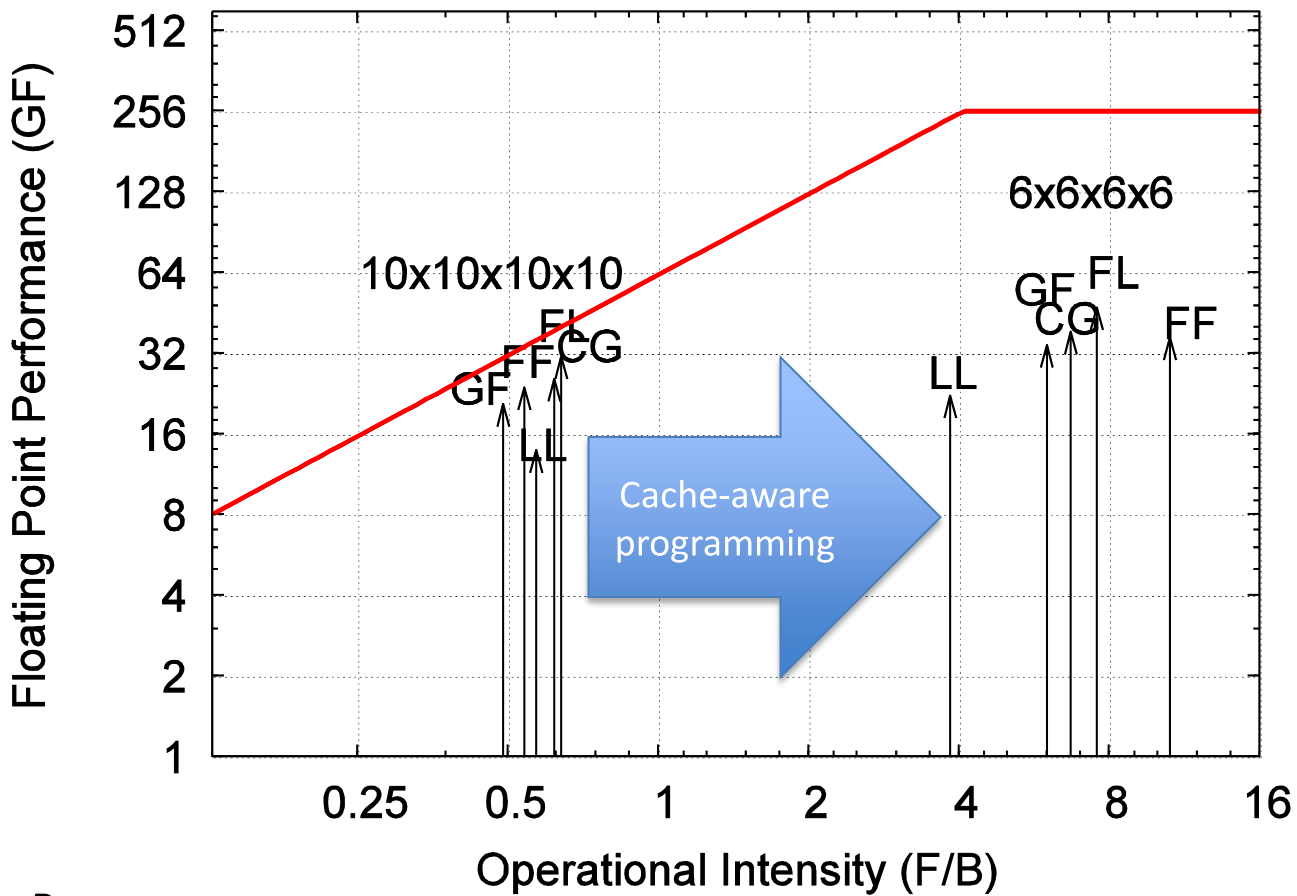
[1]: Bauer et al.: "Performance Modeling and Comparative Analysis of the MILC Lattice QCD Application su3 rmd", CCGrid'12

MILC Balance?



Thanks to Greg Bauer

MILC BALANCE?



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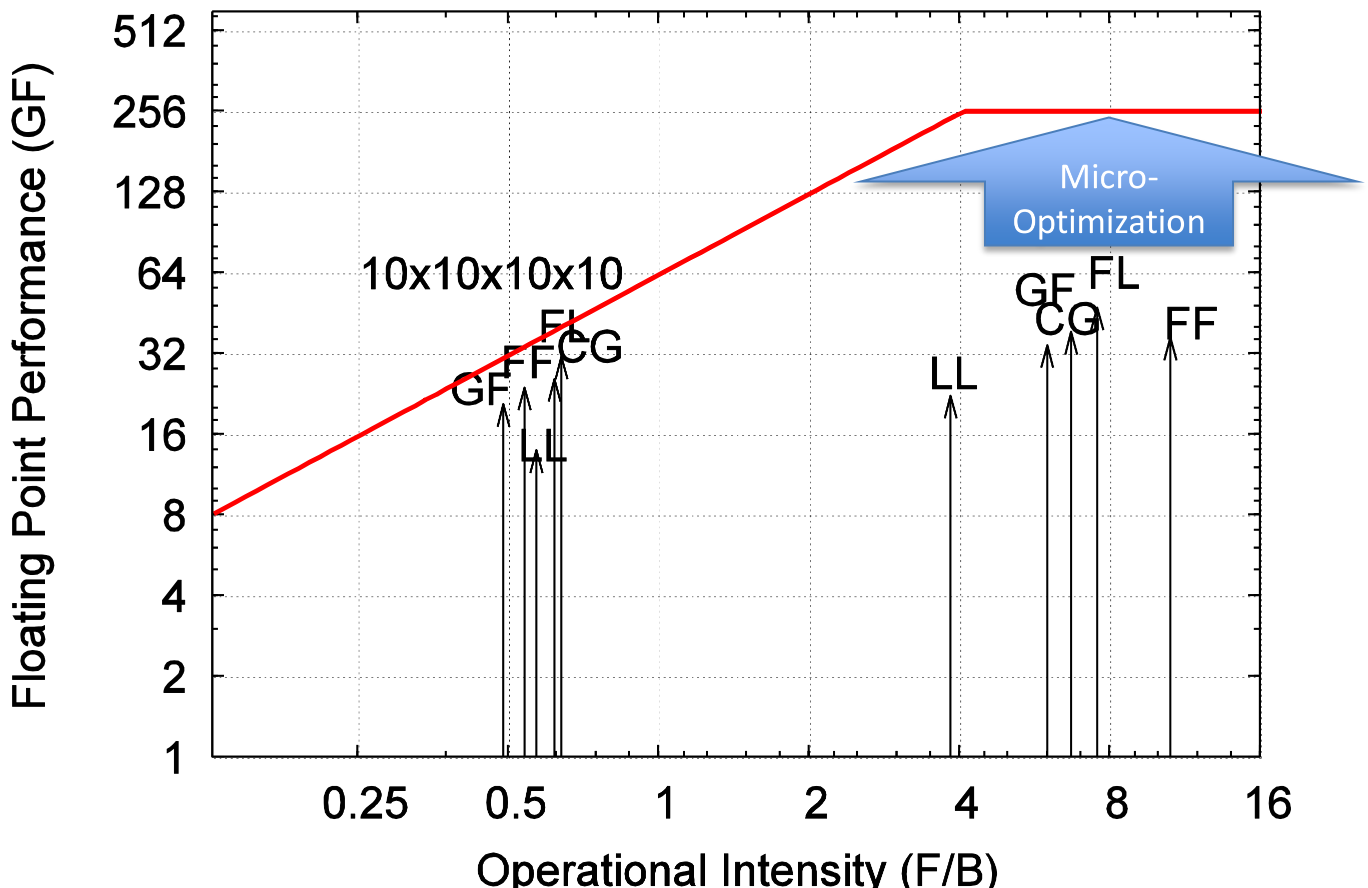
MILC BALANCE?



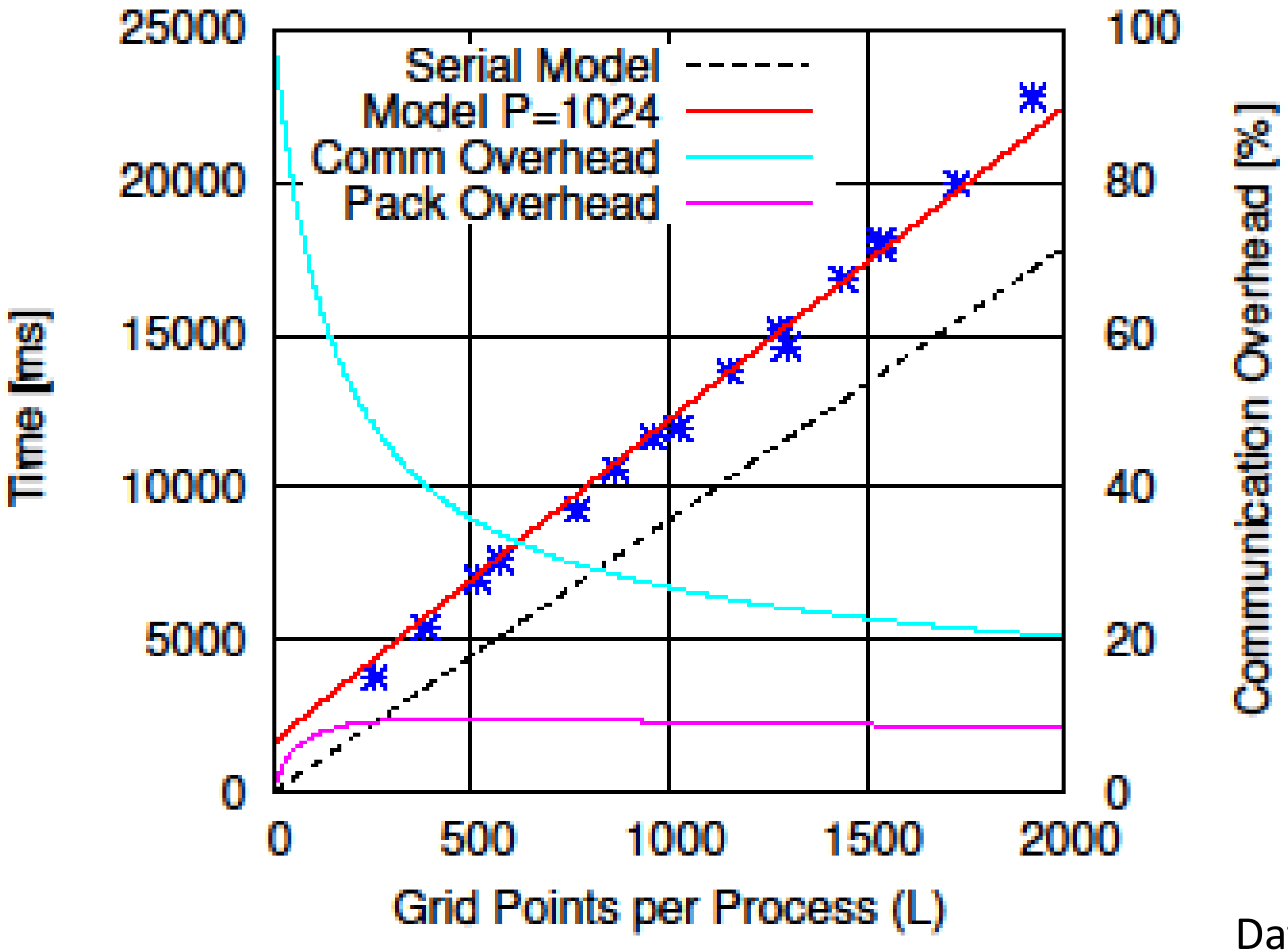
Thanks to Greg Bauer

Simple! What are the Pitfalls?

- Simple strategy for requirements modeling for co-design, isn't it?
  - Can be used by system designers and architects
- Issues:
  - Underestimated requirement functions
    - Working on it, e.g., bug finding!
  - Overlooked requirement dimensions
    - Misguided optimization/-benchmarking!
    - E.g.: Serialization overheads, Routing issues

[1]: Hoefler et al.: "Performance modeling for systematic performance tuning", SC'11

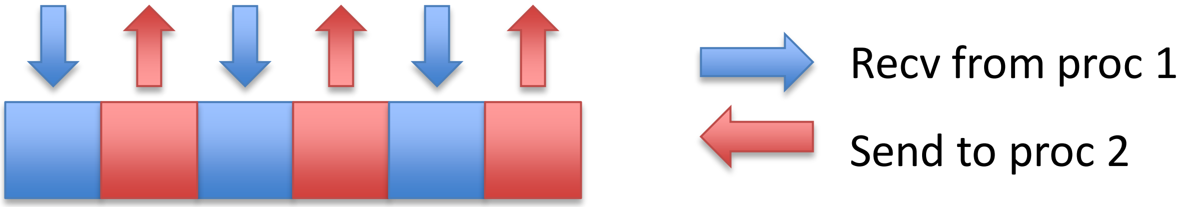
MILC: Full Performance Model



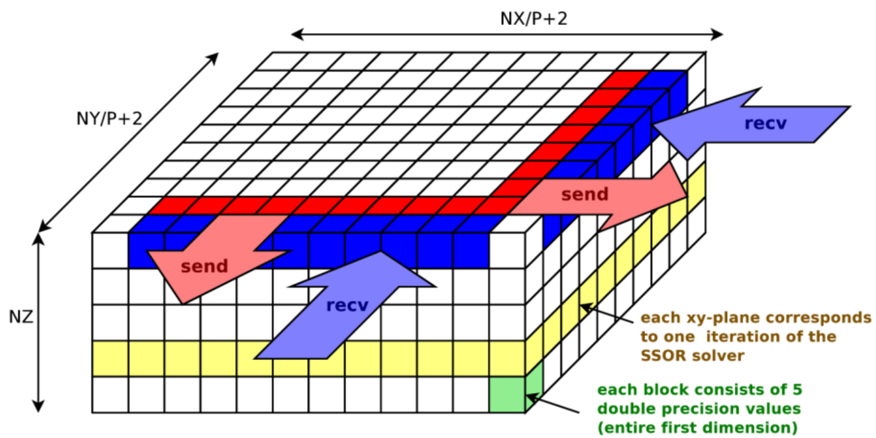
Data from POWER5

Missed Requirement I: Data Serialization

- Networks channels are serial!
- But you want to communicate this pattern:

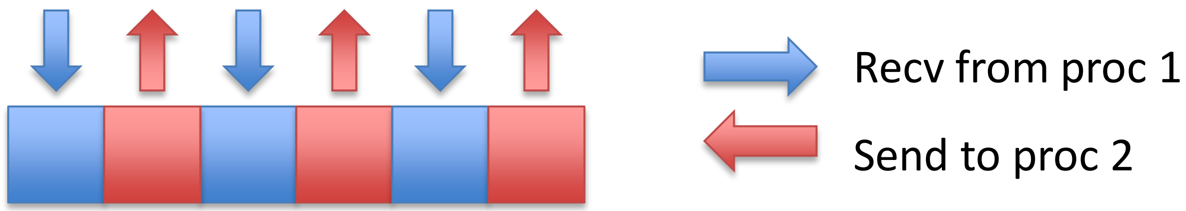


- Or a face- (Cartesian boundary-) exchange:



[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

Missed Requirement I: Data Serialization



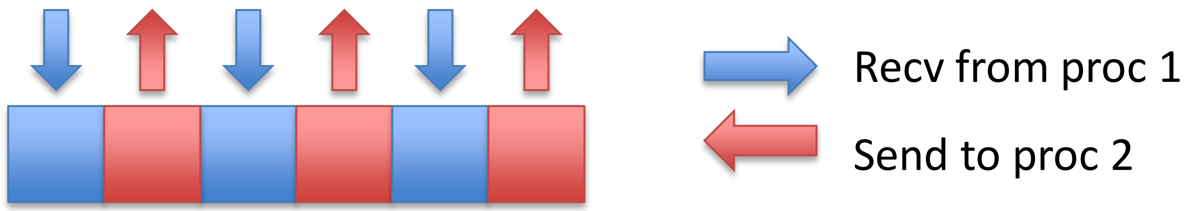
Manual Packing

```
sbuf = malloc(N/2*sizeof(int));
rbuf = malloc(N/2*sizeof(int));
for (i=1; i<N; i+=2) sbuf[i/2]=data[i];
MPI_Isend(sbuf, …);
MPI_Irecv(rbuf, …);
MPI_Waitall(…);
for (i=0; i<N; i+=2) data[i]=rbuf[i/2];
free(sbuf); free(rbuf);
```

Allocate extra send / recv Buffers

[1]: Schneider et al.: “Micro-Applications for Communication Data Access Patterns and MPI Datatypes”, EuroMPI’12

Missed Requirement I: Data Serialization



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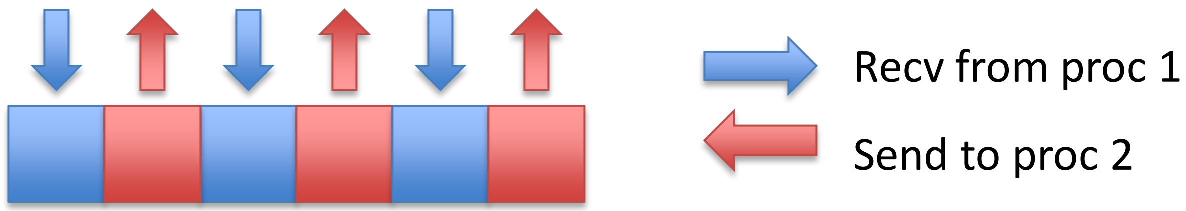
MPI_Isend(sbuf, …);
MPI_Irecv(rbuf, …);
MPI_Waitall(…);
for (i=0; i<N; i+=2) data[i]=rbuf[i/2];
free(sbuf); free(rbuf);
```

Copy data to / from extra send / recv Buffers

[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

Missed Requirement I: Data Serialization



Manual Packing

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sbuf = malloc(N/2*sizeof(int));
rbuf = malloc(N/2*sizeof(int));
for (i=1; i<N; i+=2) sbuf[i/2]=data[i];
MPI_Isend(sbuf, …);
MPI_Irecv(rbuf, …);
MPI_Waitall(…);
for (i=0; i<N; i+=2) data[i]=rbuf[i/2];
free(sbuf); free(rbuf);
```
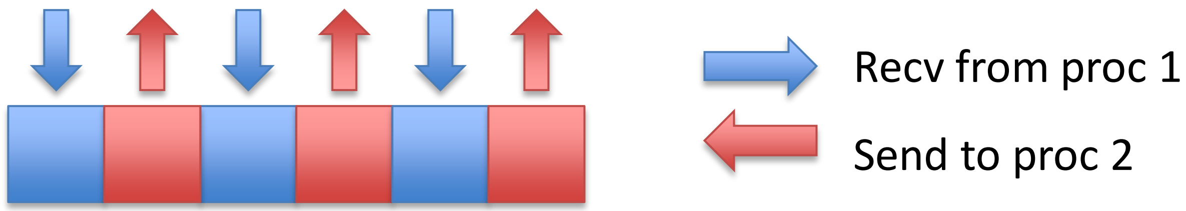

Actual sending

[1]: Schneider et al.: “Micro-Applications for Communication Data Access Patterns and MPI Datatypes”, EuroMPI’12

Missed Requirement I: Data Serialization



Manual Packing

```
sbuf = malloc(N/2*sizeof(int));
rbuf = malloc(N/2*sizeof(int));
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MPI_Isend(sbuf, …);
MPI_Irecv(rbuf, …);
MPI_Waitall(…);
for (i=0; i<N; i+=2) data[i]=rbuf[i/2];
free(sbuf);
free(rbuf);
```

MPI Datatypes

```
MPI_Datatype nt;
MPI_Type_vector(n/2, 1, 2, MPI_INT, &nt);
MPI_Type_commit(&nt);
MPI_Isend(&data[1], 1, nt, …);
MPI_Irecv(&data[0], 1, nt, …);
MPI_Waitall(…);
MPI_Type_free(&nt);
```

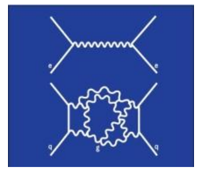
- No explicit copying
- Less code

[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

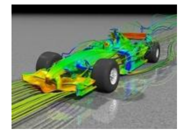
Serialization Access Patterns

Application Classes

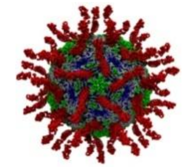
Atmospheric Science (WRF)



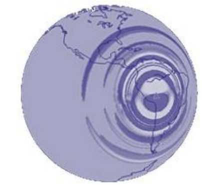
Quantumchro-Modynamics (MILC_su3)



Computational Fluiddynamics (NAS LU + MG)

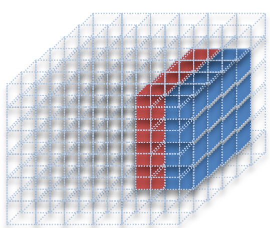


Molecular Dynamics (LAMMPS, MiniMD)

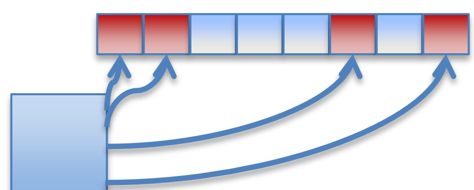


Geophysical Science (SPECFEM3D)

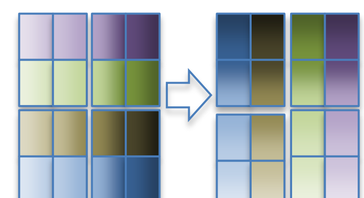
Access Patterns



Face Exchanges



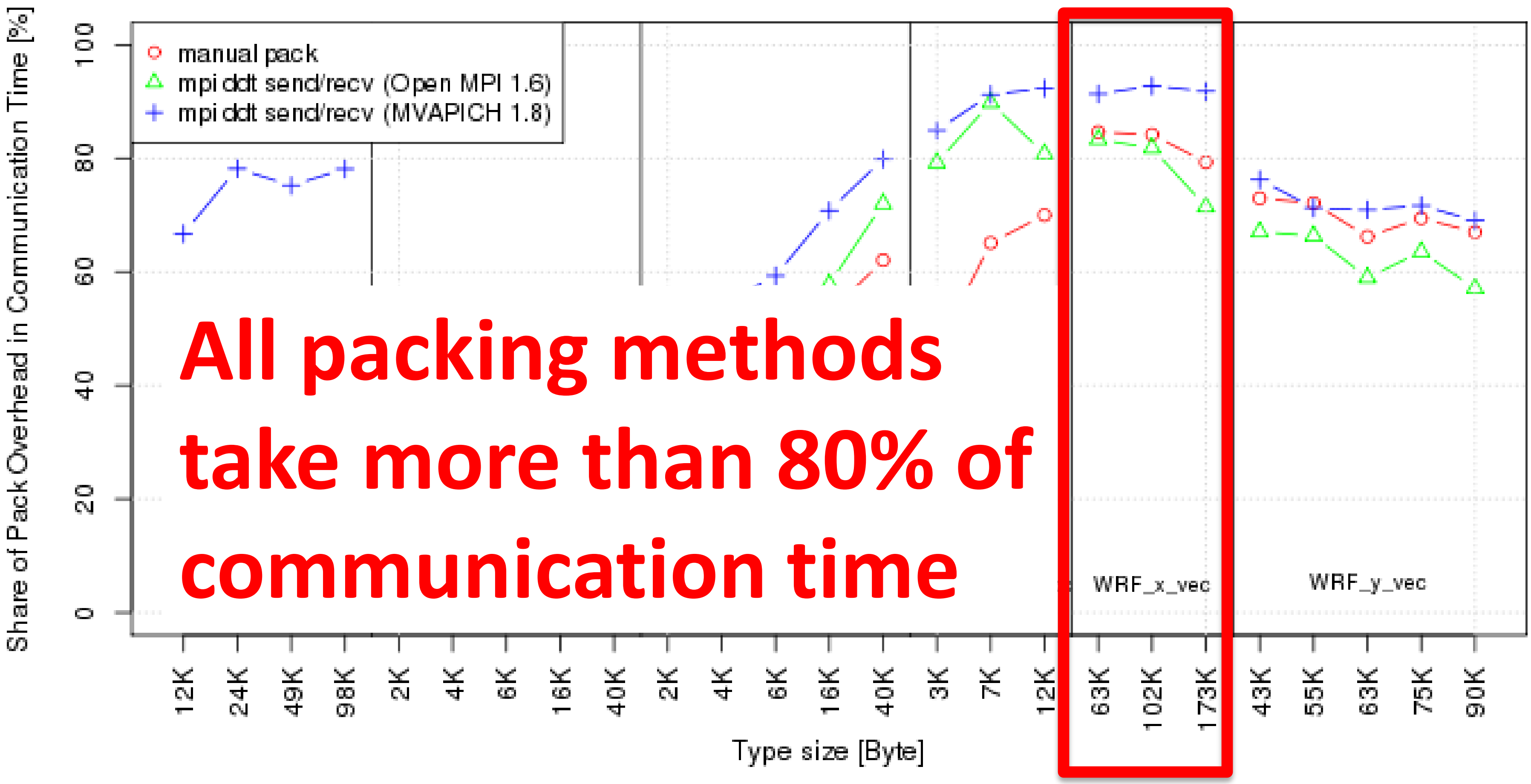
Unstructured Exchange



Matrix Transposition

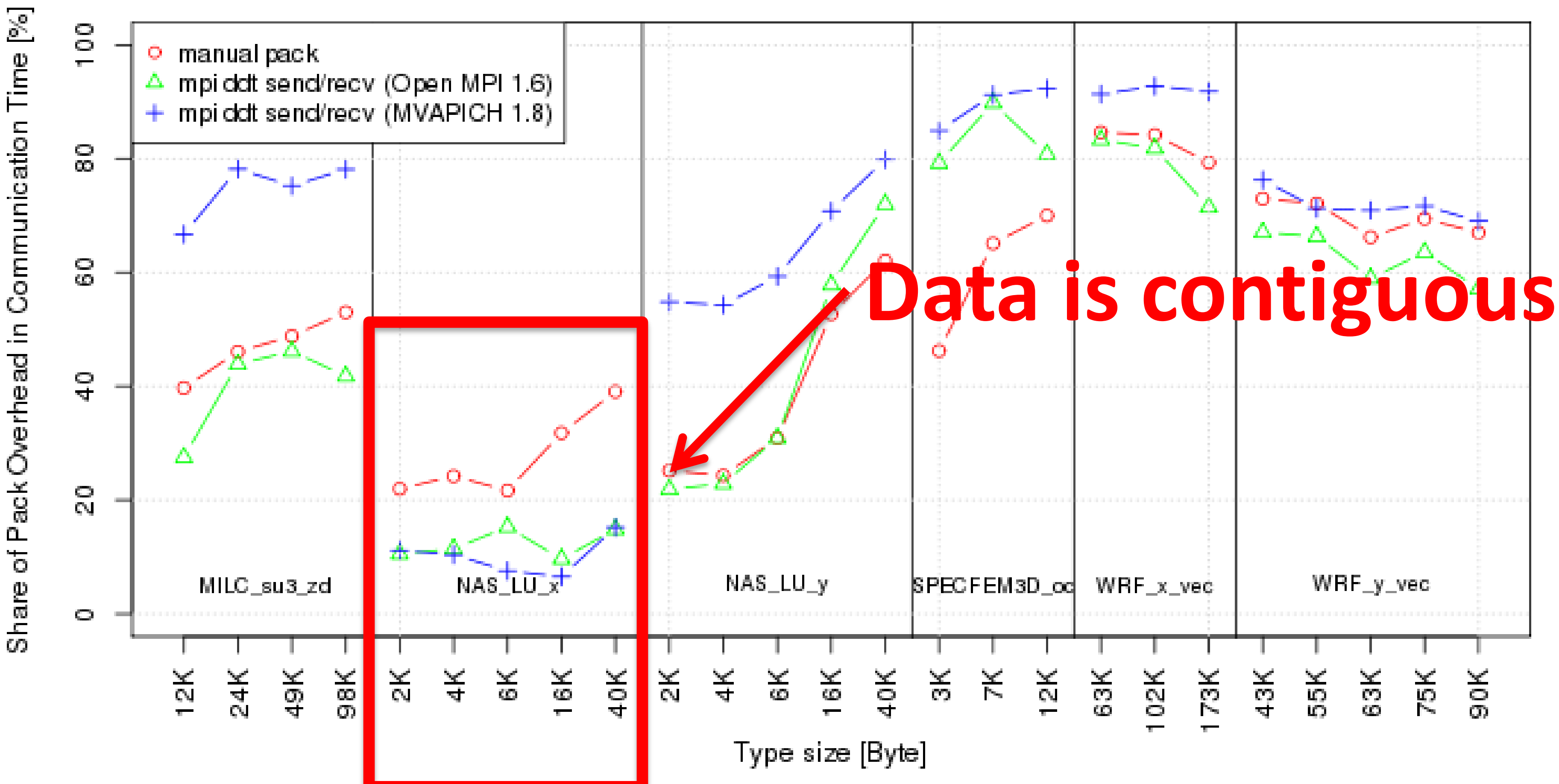
[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

Serialization Benchmark Results



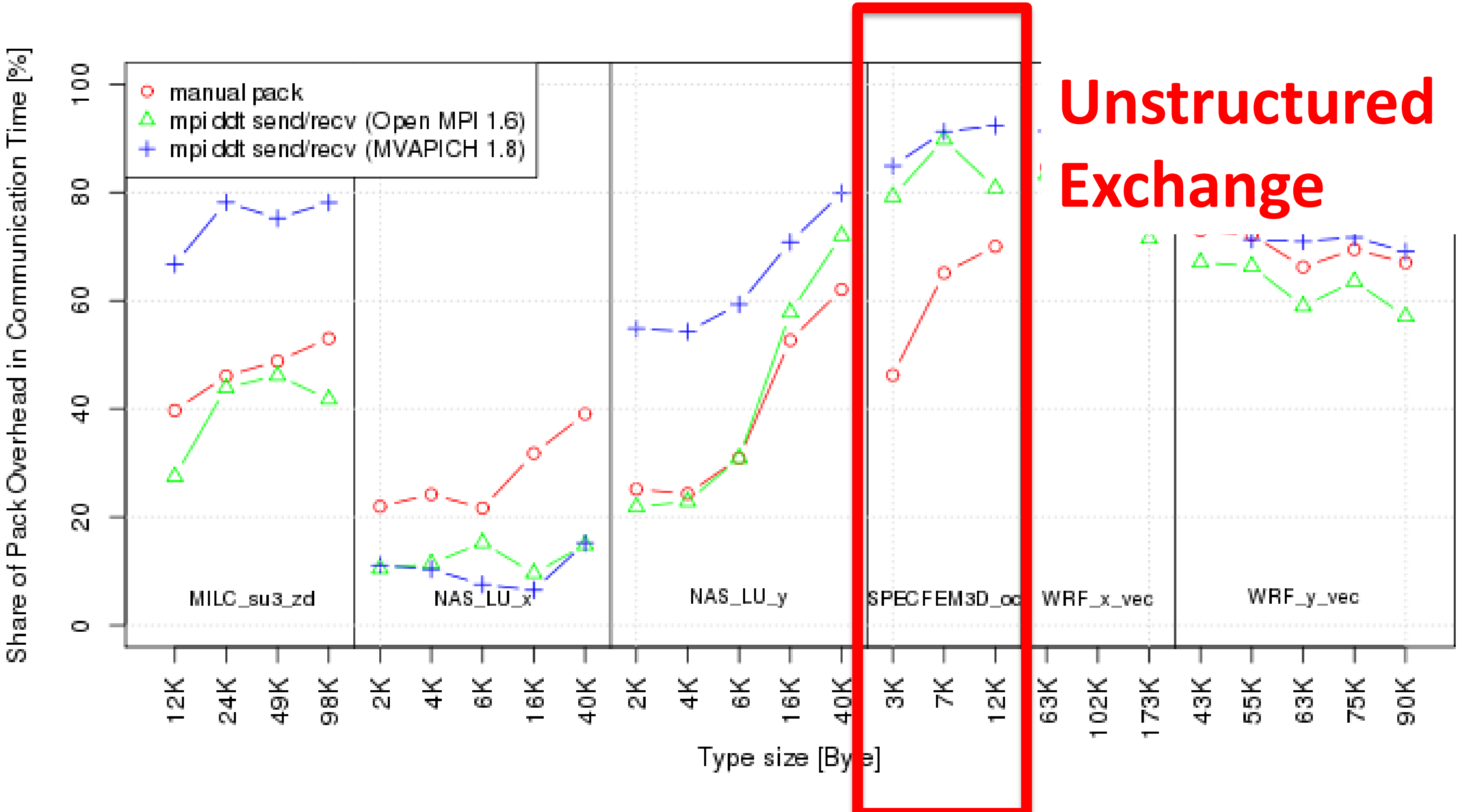
[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

Serialization Benchmark Results



[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

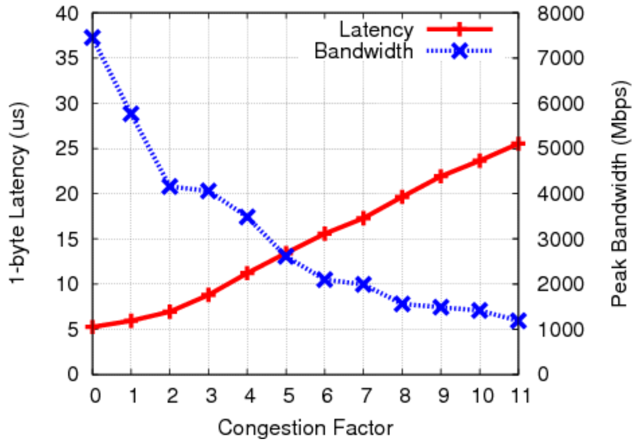
SERIALIZATION BENCHMARK RESULTS



[1]: Schneider et al.: "Micro-Applications for Communication Data Access Patterns and MPI Datatypes", EuroMPI'12

Missed Requirement II: Global Bandwidth

- Observed bandwidth < peak bandwidth
- Example [1]:
  - IB full bisection bandwidth fat tree
  - Effective bandwidth: 69% of peak
  - Reason: static routing



- Conjecture:
  - Routing needs to be co-designed [2]
    - With applications and topologies (complex topic)

[1]: Hoefler et al.: "Multistage Switches are not Crossbars: Effects of Static Routing in High-Performance Networks", Cluster'08
[2]: Prisacari et al.: "Bandwidth-optimal Alltoall Exchanges in Fat Tree Networks", ICS'13

CONCLUSIONS

- Co-design is becoming more important
- Requirements modeling is a simple strategy!
  - Not trivial, dangers:
  - Underestimating requirements function
  - Overlooking requirements dimension
- Tool support on its way
  - As automatic as possible
  - Collaboration with GRS, SPPEXA