BLUE WATERS
SUSTAINED PETASCALE COMPUTING

Performance Modeling for Systematic Performance Tuning

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NCSA NSF GREAT LAKES CONSORTIUM FOR PETASCALE COMPUTATION

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The Perspective of a Computing Center

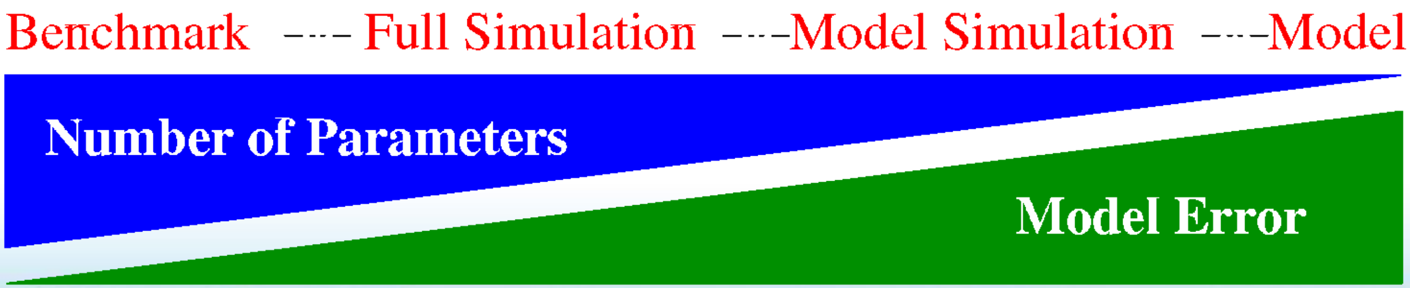
- Performance = “completed science per cost and time”
- Optimizing this metric can be manifold:
  - Application optimization (support application teams)
  - Architecture optimization (select best hardware)
  - Optimize Middleware (scheduler, libraries etc.)
  - Optimize Policies (scheduling, charging etc.)
  - … and many more

Performance Modeling – State of the Practice

- Delivers the “science per cost/time” metric
  - Can be used to drive optimizations!
- Who does performance modeling?
  - Mostly computer scientists, in-house teams
- BUT: most development is done by application developers and/or domain scientists
  - They should develop performance models during software development
    - See performance modeling panel @3:30 in TCC 101

(Ideal) State of the Practice @NCSA

- Propose to use simple performance modeling to characterize the behavior of applications
  - Enables rough optimization (cf. “80/20 rule”)
- We provide a set of simple modeling guidelines
  - Semi-analytic performance modeling
  - Small number of parameters, use other techniques where necessary



Benchmark ---- Full Simulation ----Model Simulation ----Model

Number of Parameters

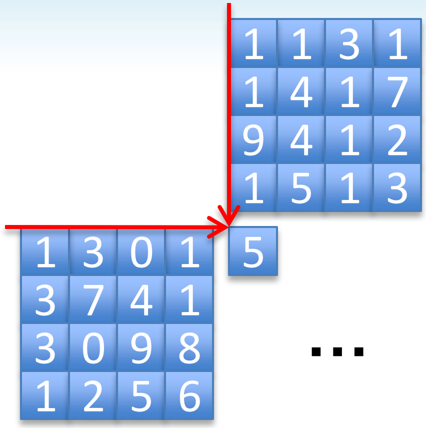
Model Error

Overview of Performance Modeling

- Analytic modeling:
  - Determine application requirements and system speeds to compute time (e.g., bandwidth)
- Empirical modeling (e.g. [1,2]):
  - “Black-box” approach: machine learning, neural networks, statistical learning …
- Semi-empirical modeling:
  - “White box” approach: find asymptotically tight analytic models, parameterize empirically (curve fitting)

[1]: Barnes, Rountree, Lowenthal, Reeves, Supinski, Schulz: A regression-based approach to scalability prediction
[2]: McKee, Singh, Supinski, Schulz: Constructing Application Performance Models Using Neural Networks

A Quick Example - MM



1	1	3	1
1	4	1	7
9	4	1	2
1	5	1	3

1	3	0	1
3	7	4	1
3	0	9	8
1	2	5	6

- Matrix multiplication (N^3 algorithm)

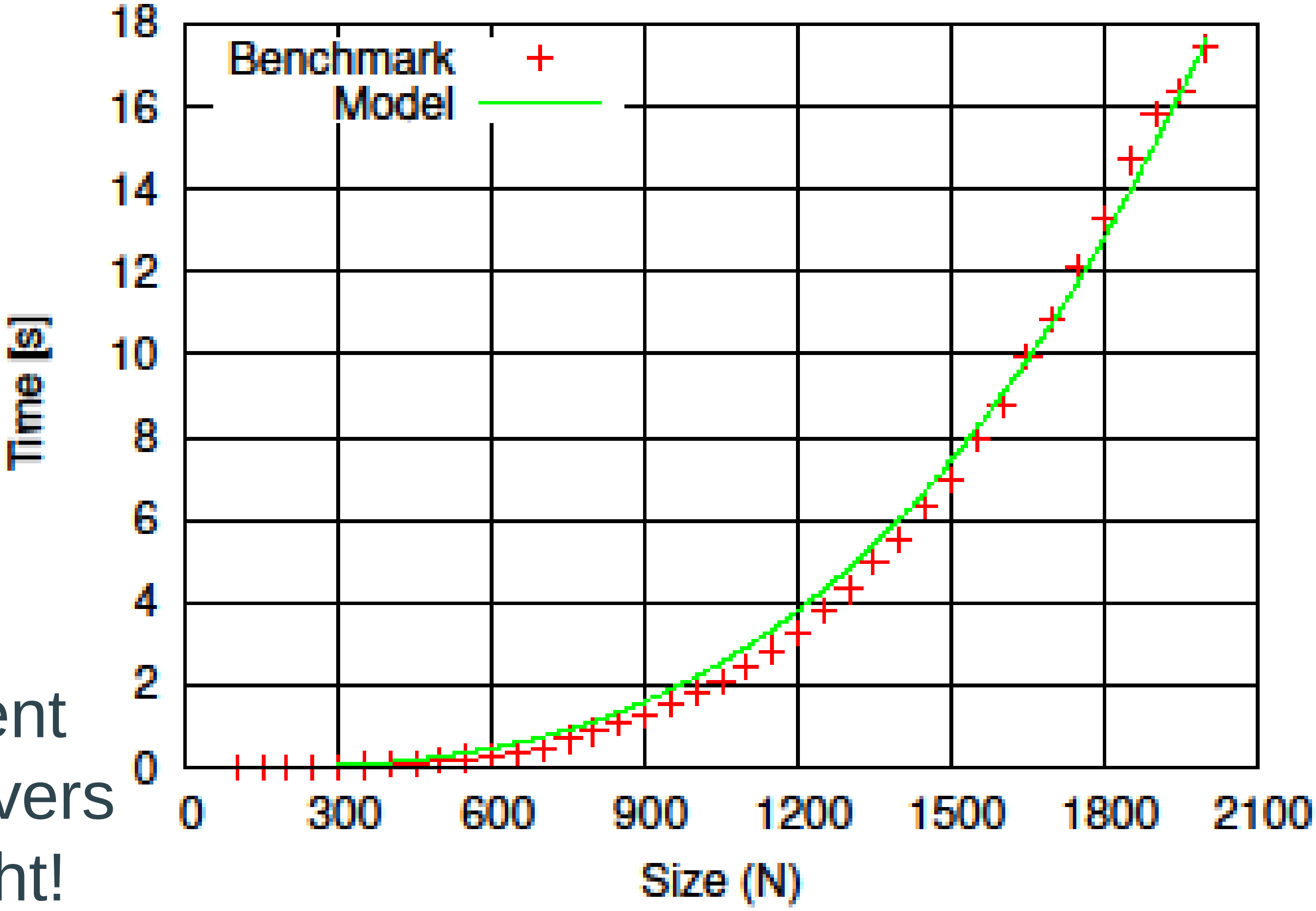
```
for(int i=0; i<N; ++i)
  for(int j=0; j<N; ++j)
    for(int k=0; k<N; ++k)
      C[i+j*N] += A[i+k*N] * B[k+j*N];
```

- Trivial (non-blocked) algorithm

- Analytic Model:
  - N^3 FP add/mult, $4N^3$ FP load/store, +int ops
  - How can we get to an execution time? → very hard!

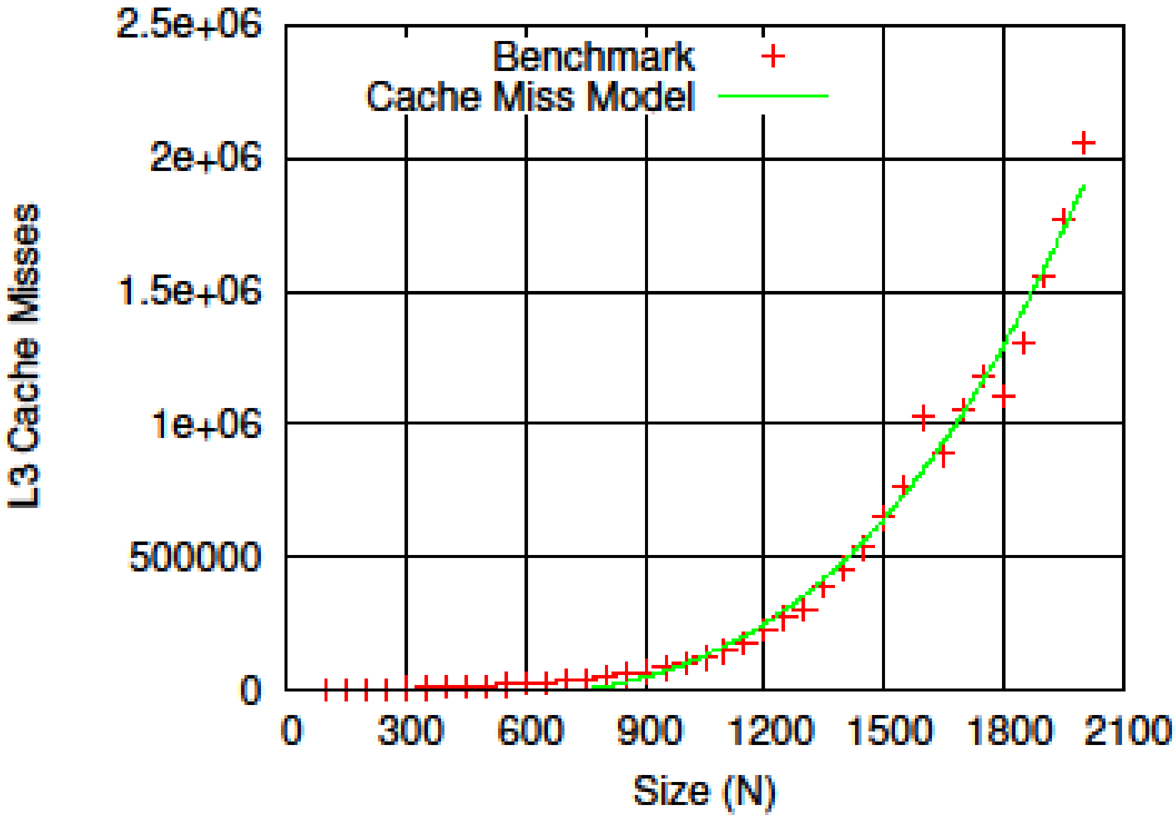
Semi-Empiric Model for MM

- $T(N) = tN^3$
- POWER7
  - t=2.2ns
  - 0.8% err
- Is that all?
  - Requirement Model delivers more insight!



Requirements Model for MM

- Required floating point operations: $2N^3$ (verified)
- Cache misses?
  - Semi-analytic!
  - $C(N) = aN^3 - bN^2$
- POWER7
  - a=3.8e-4
  - a=2.7e-1



Our Ubiquitous Modeling Philosophy

- Modeling during each phase of SW development:
  - Analysis – pick right method (asymptotic models)
  - Design – pick right algorithms (asymptotic models)
  - Implementation – show good usage of machine, e.g., blocking in MM (semi-empirical models)
  - Testing – fulfilling model expectations as correctness criterion (compare tests with models)
  - Maintenance – monitor performance on different architectures (compare times with models)

More uses of Models

- Performance Optimization
  - Identify bottlenecks and problems during porting
- System Design
  - Co-design based on application requirements
- System Deployment and Testing
  - Know what to expect, find performance issues quickly
- During System Operation
  - Detect silent (and slow) performance degradation

Six-Steps to a Model

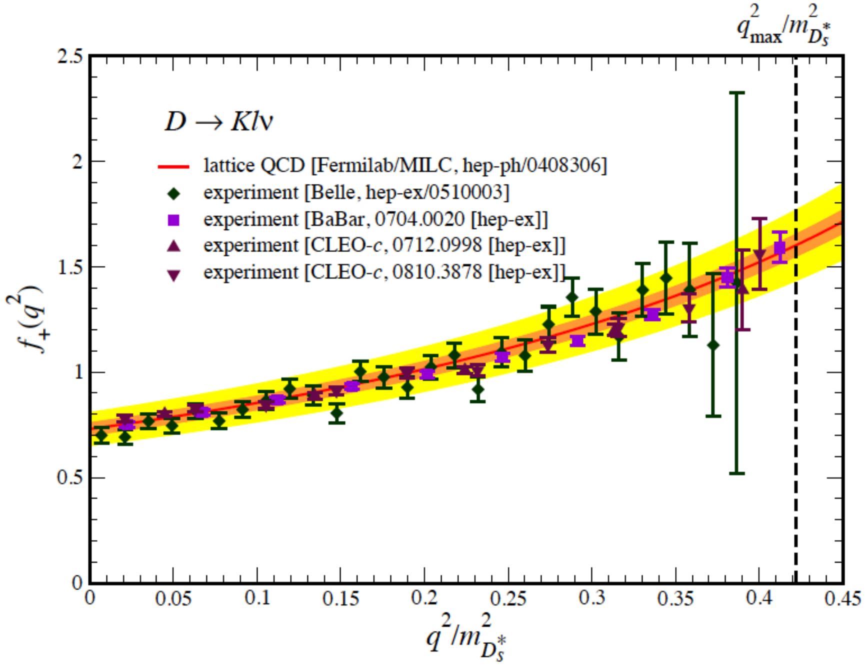
- Our <u>very</u> high-level strategy consists of the following six steps:
  1) Identify input parameters that influence runtime
  2) Identify application kernels
  3) Determine communication pattern
  4) Determine communication/computation overlap

Analytic

  5) Determine sequential baseline
  6) Determine communication parameters

Empiric

All Steps By Example – MILC



- MIMD Lattice Computation
  - Gains deeper insights in fundamental laws of physics
  - Determine the predictions of lattice field theories (QCD & Beyond Standard Model)
  - Major NSF application
- Challenge:
  - High accuracy (computationally intensive) required for comparison with results from experimental programs in high energy & nuclear physics

Bernard, Gottlieb et al.: Studying Quarks and Gluons On Mimd Parallel Computers

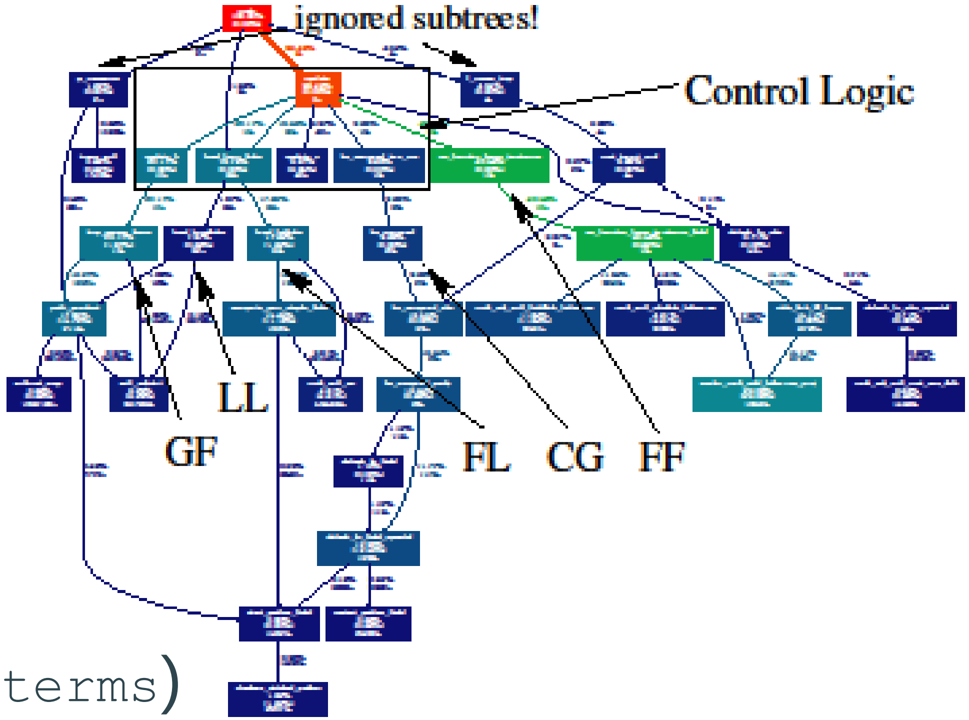
Step 1: Critical Parameters

- Best way: ask a domain expert!
  - Or: look through the code/input file format
- For MILC (thanks to S. Gottlieb):

Name	**Description**
P	number of PEs (intrinsic parameter)
nx, ny, nz, nt	size in x, y, z, t dimension
warms, trajecs	warmup rounds and trajectories (outer loop)
traj_between_meas	measurement "frequency"
steps_per_trajectory	number of "steps" in each trajectory
beta, mass1, ...	physics parameters that influence CG iterations
max_cg_iterations	limits the conjugate gradient iterations

Step 2: Find Kernels

- E.g., investigate call-tree or source-code
- Control logic
  - `update`
- MILC's kernels:
  - LL (`load_longlinks`)
  - FL (`load_fatlinks`)
  - CG (`ks_congrad`)
  - GF (`imp_gauge_force`)
  - FF (`eo_fermion_force_twoterms`)

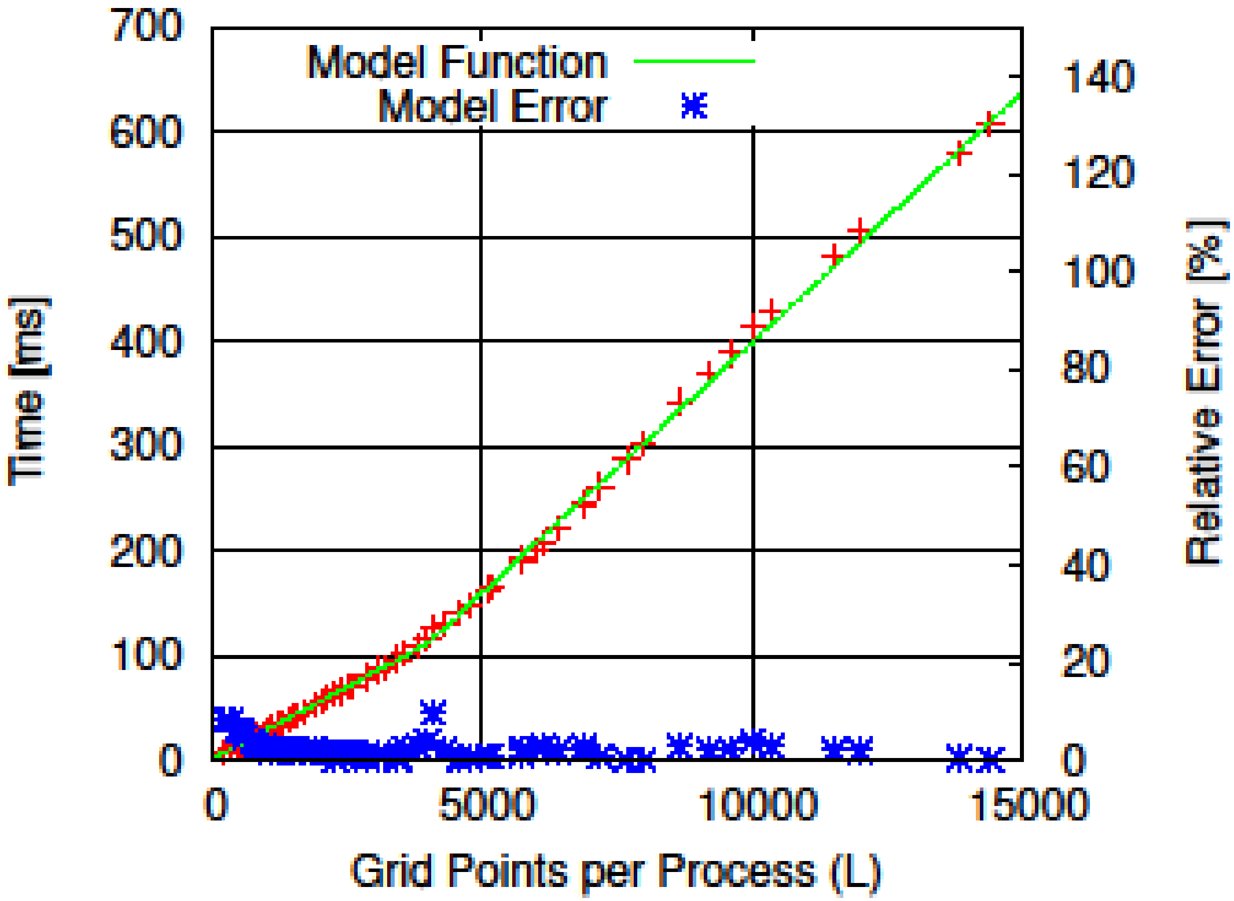


Step 4: Sequential Performance

- MILC “only” loops over the lattice → $\Theta(V)$
- ➢ $T(V) = tV$
  - Wait, it’s not that simple with caches ☹
  - Small V fit in cache!
- ➢ $T(V) = t_1 * \min(s, V) + t_2 * \max(0, V-s)$
  - Cache holds s data elements
  - Three parameters for each kernel

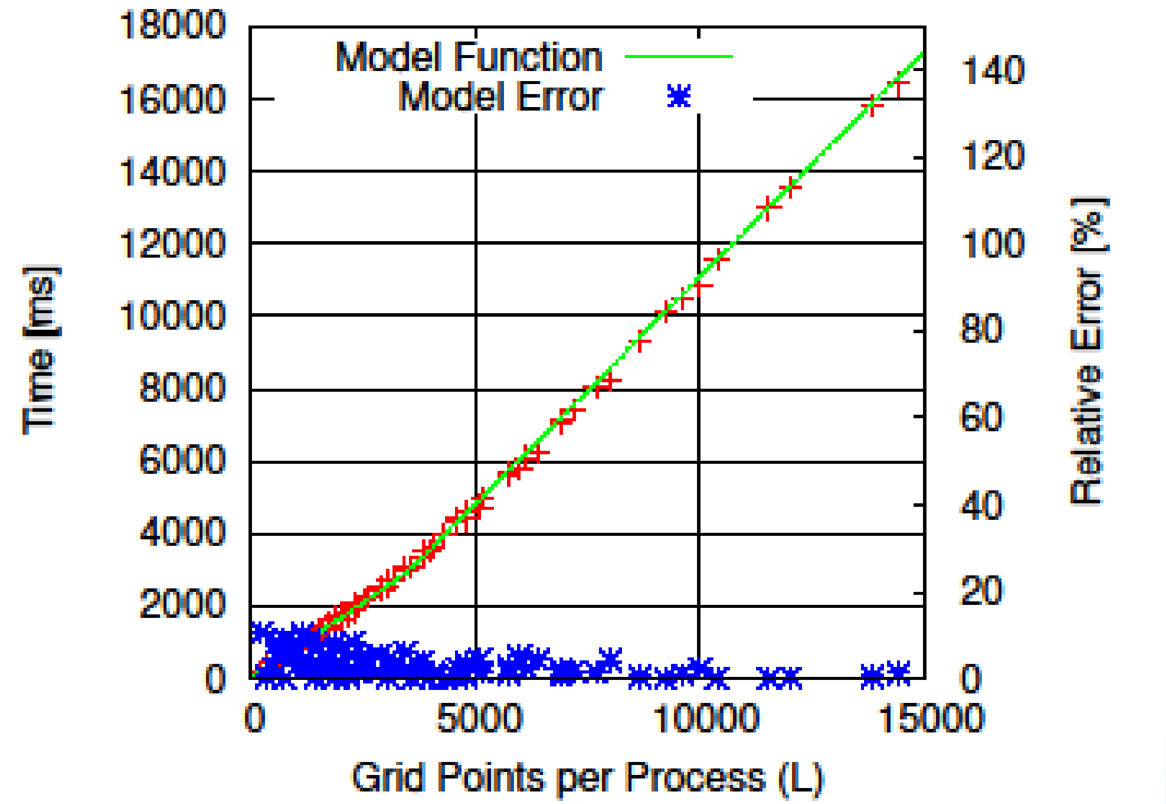
An Example Kernel: GF (Gauge Force)

- On POWER7:
  - t_1=62.4 µs
  - t_2=92 µs
  - s=4.000
- Errors
  - Max <10%
  - Cum <3%



Complete Serial Performance Model

$$T_{serial}(V) = (\mathtt{trajecs} + \mathtt{warms}) \cdot \mathtt{steps} \cdot [T(FF,V) + T(GF,V) + 3(T(LL,V) + T(FL,V))] + \left\lfloor \frac{\mathtt{trajecs}}{\mathtt{meas}} \right\rfloor [T(LL,V) + T(FL,V)] + \mathtt{niters} \cdot T(CG,V)$$



Step 3: Communication Pattern

- 4d domain is cut in all dimensions (cubic)
  - 4d nearest-neighbor communication (8 neighbors)
- Allreduce to check CG convergence
  - One per iteration on full process set
- We counted messages and sizes
  - Separate for each kernel
  - See paper for sizes and full model equation!

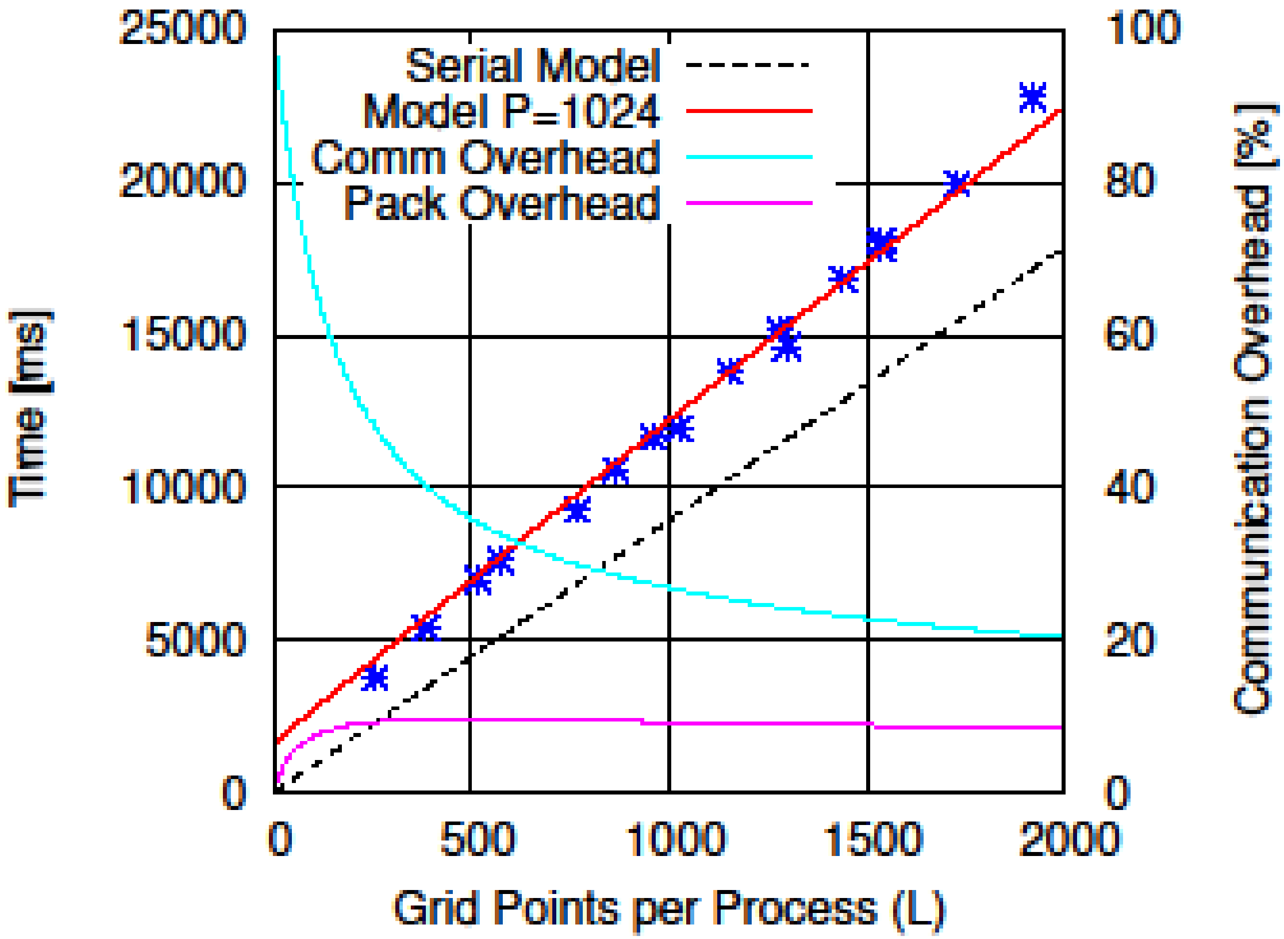
kernel	$\#Messages$
FF	$(\texttt{trajecs} + \texttt{warms}) \cdot \texttt{steps} \cdot 1616$
GF	$(\texttt{trajecs} + \texttt{warms}) \cdot \texttt{steps} \cdot 828$
LL	$(3 \cdot \texttt{steps} \cdot (\texttt{trajecs} + \texttt{warms}) + \lfloor \frac{\texttt{trajecs}}{\texttt{meas}} \rfloor) \cdot 8$
FL	$(3 \cdot \texttt{steps} \cdot (\texttt{trajecs} + \texttt{warms}) + \lfloor \frac{\texttt{trajecs}}{\texttt{meas}} \rfloor) \cdot 288$

Step 6: Communication Parameters

- Two options:
  - Semi-empiric – fit measurements to get effective latency and bandwidth
    - Enables to check if they match expectations
  - Analytic – derive parameters separately (e.g., documentation or separate benchmark)
    - Often problematic if they do not match expectations
- Our model was analytic
  - Uses LogGP parameters (measured by Netgauge [1])

[1] Hoefler et al.: Low-Overhead LogGP Parameter Assessment for Modern Interconnection Networks

The Fully-Parameterized Parallel Model



Conclusions and Future Work

- Models in use for predictions and optimizations
  - First successes: ~10-20% improved performance [1]
- Simple strategy enables application team models
  - Better chance to be maintained than external models
  - Critical for performance-centric software development
- We need (and work on):
  - More examples for irregular/dynamic codes
  - Better tool support for modeling

[1] Hoefler, Gottlieb.: Parallel Zero-Copy Algorithms for Fast Fourier Transform and Conjugate Gradient using MPI Datatypes