X-TUNE
Autotuning for Exascale: Self-Tuning Software to Manage Heterogeneity

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Website:
http://ctop.cs.utah.edu/x-tune/

Exascale Software: A View in 2012

Thanks to exascale reports and workshops

- Multiresolution programming systems for different users
  - Joe/Stephanie/Doug **[Pingali, UT]**
  - Elvis/Mort/Einstein **[Intel]**
- Specialization simplifies and improves efficiency
  - Target specific user needs with domain-specific languages/libraries
  - Customize libraries for application needs and execution context
- Interface to programmers and runtime/hardware
  - Seamless integration of compiler with programmer guidance and dynamic feedback from runtime
- Toolkits rather than monolithic systems
  - Layers support different user capability, collaborative ecosystem
- Virtualization (over-decomposition)
  - Hierarchical, or flat but construct hierarchy when applicable?

What is Autotuning?

- Definition:
  - Automatically generate a "search space" of possible implementations of a computation
    - A ***code variant*** represents a unique implementation of a computation, among many
    - A ***parameter*** represents a discrete set of values that govern code generation or execution of a variant
  - Measure execution time and compare
  - Select the best-performing implementation (for exascale, tradeoff between performance/energy/reliability)
- Key Issues:
  - Identifying the search space
  - Pruning the search space to manage costs
  - Off-line vs. on-line search

Three Types of Autotuning Systems

a. Autotuning libraries
   - Library that encapsulates knowledge of its performance under different execution environments
   - Dense linear algebra: **ATLAS, PhiPAC**
   - Sparse linear algebra: **OSKI**
   - Signal processing: **SPIRAL, FFTW**

X-TUNE

b. Application-specific autotuning
   - **Active Harmony** provides parallel rank order search for tunable parameters and variants
   - **Sequoia** and **PetaBricks** provide language mechanism for expressing tunable parameters and variants

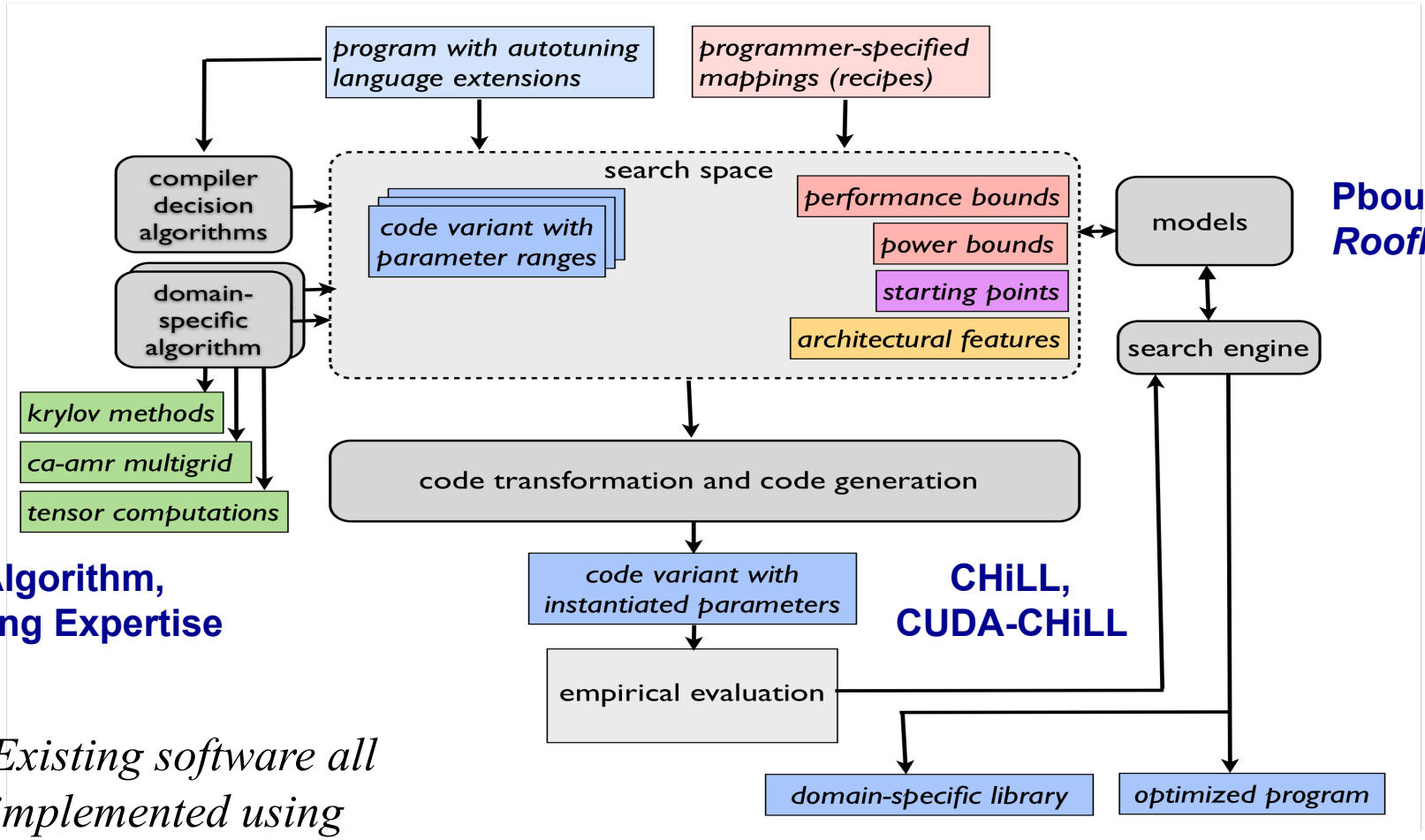
c. Compiler-based autotuning
   - Other examples: Saday et al., Swany et al., Eignenmann et al.
   - Related concepts: iterative compilation, learning-based compilation

X-TUNE Goals

A unified autotuning framework that seamlessly integrates programmer-directed and compiler-directed autotuning,

- Expert programmer and compiler work collaboratively to tune a code.
  - Unlike previous systems that place the burden on either programmer or compiler.
  - Provides access to compiler optimizations, offering expert programmers the control over optimization they so often desire.
- Design autotuning to be encapsulated in domain-specific tools
  - Enables less-sophisticated users of the software to reap the benefit of the expert programmers' efforts.
- Focus on Adaptive Mesh Refinement Multigrid (Combustion Co-Design Center,BoxLib,Chombo) and tensor contractions (TCE)

X-TUNE Structure



Existing software all implemented using ROSE AST.

Autotuning Language Extensions

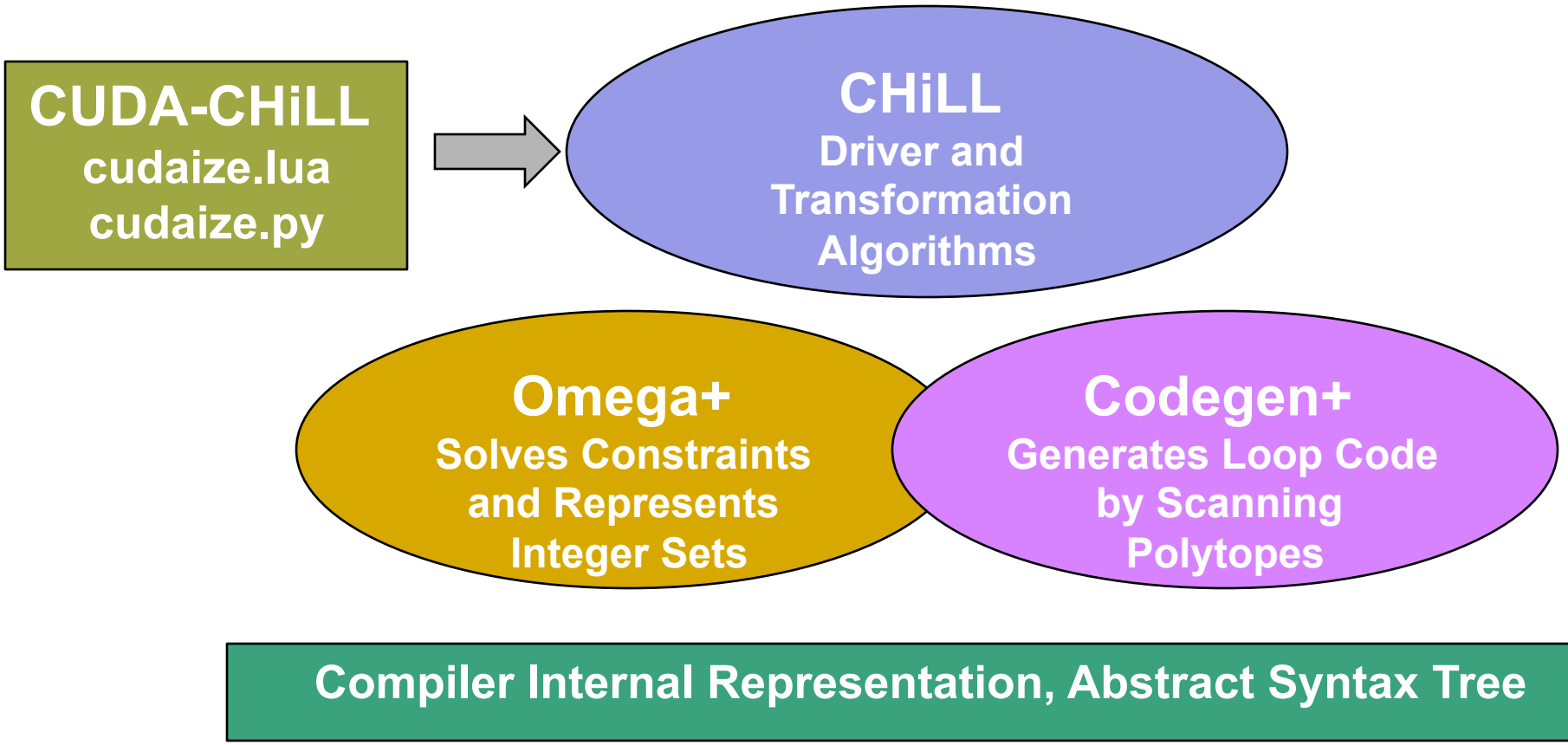
- **Tunable Variables**
  - An annotation on the type of a variable (as in Sequoia)
  - Additionally, specify range, constraints and a default value
- **Computation Variants**
  - An annotation on the type of a function (as in PetaBricks)
  - Additionally, specify (partial) selection criteria
  - Multiple variants may be composed in the same execution

Separate mapping description captures architecture-specific aspects of autotuning.

Compiler-Based Autotuning

- ***Foundational Concepts***
  - Identify search space through a high-level description that captures a large space of possible implementations
  - Prune space through compiler domain knowledge and architecture features
  - Provide access to programmers with **transformation recipes**, or recipes generated automatically by compiler decision algorithm
  - Uses source-to-source transformation for portability, and to leverage vendor code generation
  - Requires ***restructuring of the compiler***

CHiLL Implementation



Transformation Recipes for Autotuning: Incorporate the Best Ideas from Manual Tuning

Nvidia GTX-280 implementation
Mostly corresponds to CUBLAS 2.x and Volkov's SC08 paper

```
1 tile_by_index({"i","j"},{TI,TJ},{l1_control="ii",l2_control="jj"},
                {"ii","jj","i","j"})
2 tile_by_index({"k"},{TK},{l1_control="kk"},
                {"ii","jj","kk","i","j","k"},strided)
3 tile_by_index({"i"},{TJ},{l1_control="tt",l1_tile="t"},
                {"ii","jj","kk","t","tt","j","k"})
4 cudaize("mm_GPU",{a=N*N,b=N*N,c=N*N},
          {block={"ii","jj"},thread={"t","tt"}})
5 copy_to_shared("tx","b",-16)
6 copy_to_registers("kk","c")
7 copy_to_texture("b")
8 unroll_to_depth(2)
```

```
1  tile_by_index({"i","j"},{TI,TJ},{l1_control="ii",l2_control="jj"},
                 {"ii","jj","i","j"})
2  tile_by_index({"k"},{TK},{l1_control="kk"},
                 {"ii","jj","kk","i","j","k"},strided)
3  tile_by_index({"i"},{TK},{l1_control="t",l1_tile="tt"},
                 {"ii","jj","kk","tt","t","j","k"})
4  tile_by_index({"j"},{TK},{l1_control="s",l1_tile="ss"},
                 {"ii","jj","kk","tt","t","ss","s","k"})
5  cudaize("mm_GPU",{a=N*N,b=N*N,c=N*N},
           {block={"ii","jj"},thread={"tt","ss"}})
6  copy_to_shared("tx","b",-16)
7  copy_to_texture("b")
8  copy_to_shared("tx","a",-16)
9  copy_to_texture("a")
10 copy_to_registers("kk","c")
11 unroll_to_depth(2)
```

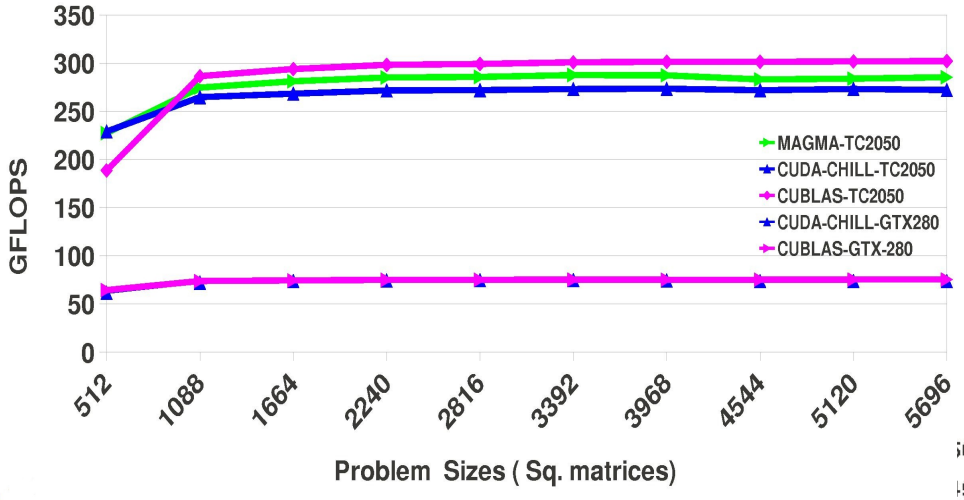
Nvidia TC2050 Fermi implementation
Mostly corresponds to CUBLAS 3.2 and MAGMA

Different computation decomposition leads to additional tile command

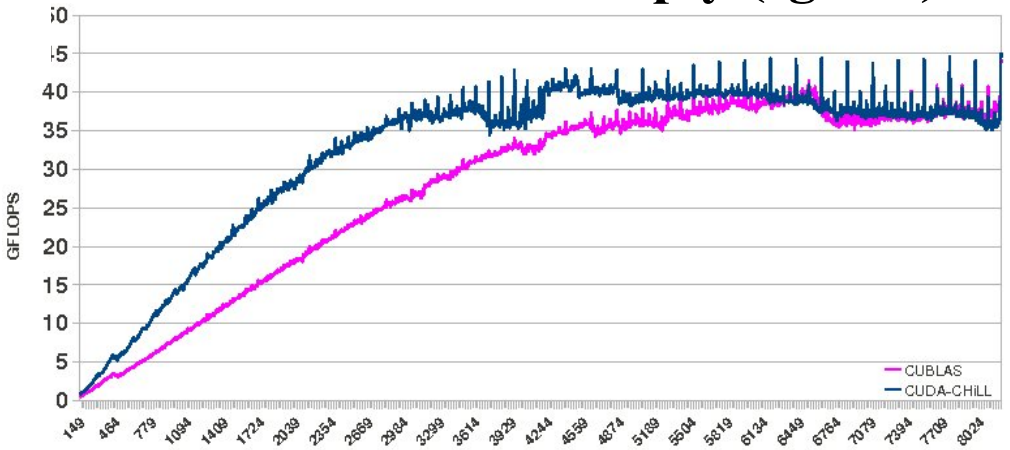
a in shared memory, both a and b are read through texture memory

Compiler + Autotuning can yield comparable and even better performance than manually-tuned libraries

Matrix-Matrix Multiply (dgemm)



Matrix-Vector Multiply (sgemv)



- Performance comparison with CUBLAS 3.2

"Autotuning, Code Generation and Optimizing Compiler Technology For GPUs," M. Khan, PhD Dissertation, University of Southern California, May 2012.

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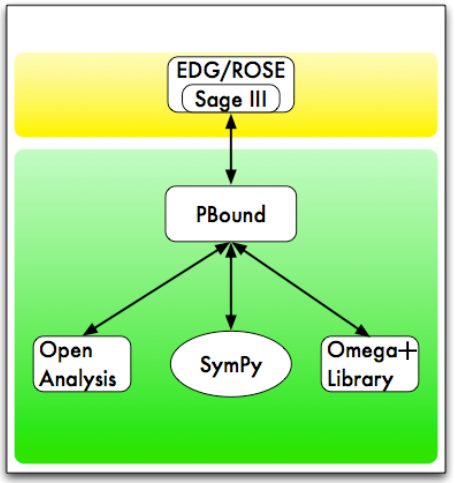
Pbound: Performance Modeling for Autotuning

- Performance modeling increases the automation in autotuning
  - Manual transformation recipe generation is tedious and error-prone
  - Implicit models are not portable across platforms



- Models can unify programmer guidance and compiler analysis
  - Programmer can invoke integrated models to guide autotuning from application code
  - Compiler can invoke models during decision algorithms
- Models optimize autotuning search
  - Identify starting points
  - Prune search space to focus on most promising solutions
  - Provide feedback from updates in response to code modifications

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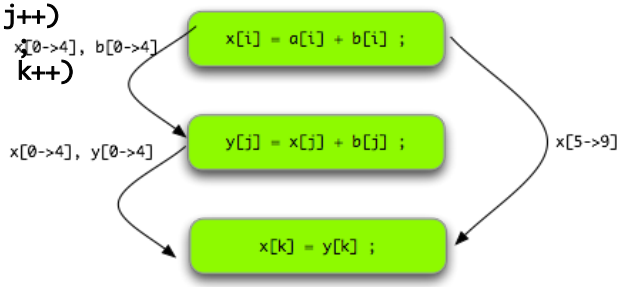
Pbound: Reuse Distance and Cache Miss Prediction

Reuse distance

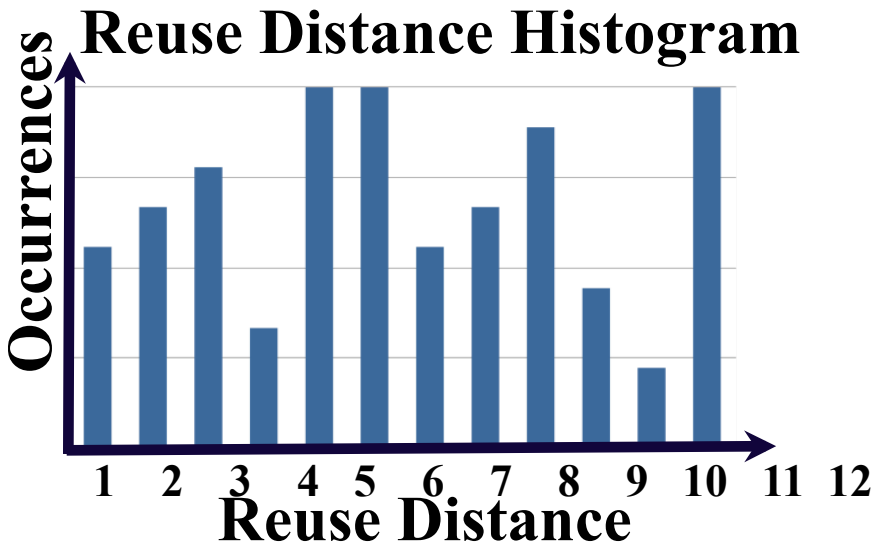
- For regular (affine) array references
  - Compute reuse distance, to predict data footprints in memory hierarchy.
  - Guides transformation and data placement decisions.

```
void foo() {
  int i, j, k, n;
  double y[10], x[10];
  double z[10], a[10], b[10];
  for (i = 0; i < 10; i++)
    x[i] = a[i] + b[i] ;
  for (j = 0; j < 5; j++)
    y[j] = x[j]+ b[j] ;
  for (k = 0; k < 10; k++)
    x[k] = y[k] ;
  return;
}
```



Cache miss prediction

- Use to predict misses
- Assuming fully associative cache with n lines (optimistic case), a reference will hit if the reuse distance d<n.



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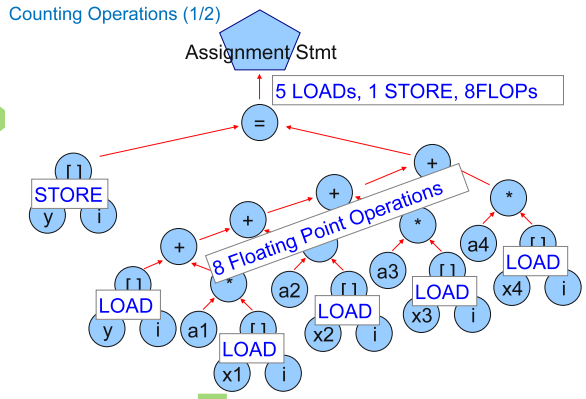
Pbound: Application signatures+architecture

```
void axpy4(int n, double *y, double a1, double *x1, double a2,
 double *x2, double a3, double *x3, double a4, double *x4) {
   register int i;
   for (i=0; i<=n-1; i++)
      y[i]=y[i]+a1*x1[i]+a2*x2[i]+a3*x3[i]+a4*x4[i];
}
```




```
#include "pbound_list.h"
void axpy4(int n, double *y, double a1, double *x1, double a2,
double *x2, double a3, double *x3, double a4, double *x4){
#ifdef pbound_log
pboundLogInsert("axpy.c@6@5",8,0,40 * ((n - 1) + 1) + 32,
          8 * ((n - 1) + 1),3 * ((n - 1) + 1) + 1,4 * ((n - 1) + 1));
 #endif
}
```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How will modeling be used?

- Single-core and multicore models for application performance will combine architectural information, user-guidance, and application analysis
- Models will be coupled with decision algorithms to automatically generate CHiLL transformation recipes
  - Input: Reuse Information, Loop Information etc.
  - Output: Set of transformation scripts to be used by empirical search
- Feedback to be used to refine model parameters and behavior
- Small and large application execution times will be considered

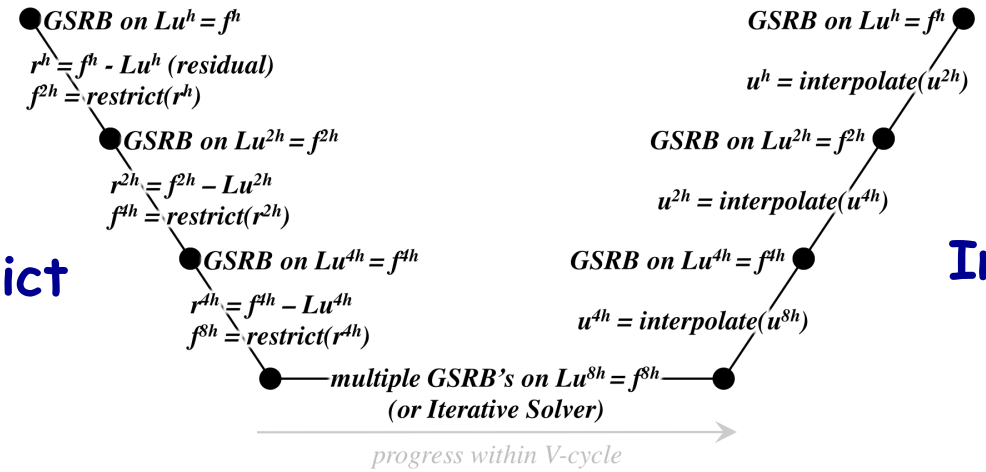
Example: Stencils and Multigrid

- Stencil performance bound, when bandwidth limited:

  Performance (gflops) <=

  stencil flops * STREAM bandwidth / grid size

- Multigrid solves Au=f by calculating a number of corrections to an initial solution at varying grid coarsenings ("V-cycle")
  - Each level in the v-cycle: perform 1-4 relaxes (~stencil sweeps).
  - Repeat multiple v-cycles reducing the norm of the residual by an order of magnitude each cycle.



Restrict

Interpolate

Solve

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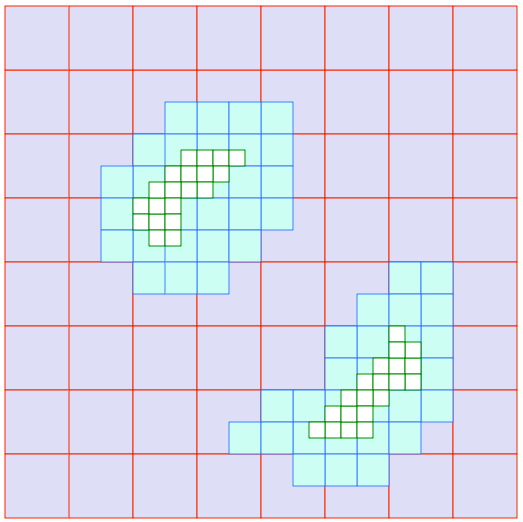
Multigrid and Adaptive Mesh Refinement



- Some regions of the domain may require finer fidelity than others.
- In Adaptive Mesh Refinement, we refine those regions to a higher resolution in time and space.
- Typically, one performs a multigrid "level solve" for one level (green, blue, red) at a time.
- Coarse-fine boundaries (neighboring points can be at different resolutions) complicate the calculation of the RHS and ghost zones for the level.
- **Each level is a collection of small (32^3 or 64^3) boxes to minimize unnecessary work.**
- These boxes will be distributed across the machine for load balancing (neighbors are not obvious/implicit)

Autotuning for AMR Multigrid

- Focus is addressing data movement, multifaceted:
  - Automate fusion of stencils within an operator. Doing so may entail aggregation of communication (deeper ghost zones)
  - Extend and automate the communication-avoiding techniques developed in CACHE.
  - Automate application of data movement-friendly coarse-fine boundary conditions.
  - Automate hierarchical parallelism within a node to AMR MG codes.
  - Explore alternate data structures
  - Explore alternate stencil algorithms (higher order, …)
- Proxy architectures: MIC, BG/Q, GPUs
- Encapsulate into an embedded DSL approach

Summary and Leverage

- Build integrated end-to-end autotuning, focused on AMR multigrid and tensor contractions
  - Language and compiler guidance of autotuning
  - Programmer and compiler collaborate to tune a code
  - Modeling assists programmer, compiler writer, and search space pruning.
- Leverage and integrate with other X-Stack teams
  - Our compiler technology all based on ROSE so can leverage from and provide capability to ROSE.
  - Domain-specific technology to facilitate encapsulating our autotuning strategies.
  - Collaborate with MIT on autotuning interface
  - Common run-time for a variety of platforms (e.g., GPUs and MIC), and supports a large number of potentially hierarchical threads.