



Lawrence Berkeley National Laboratory / National Energy Research Supercomputing Center

## Frameworks in Complex Multiphysics HPC Applications

**CS267 – Spring 2015**  
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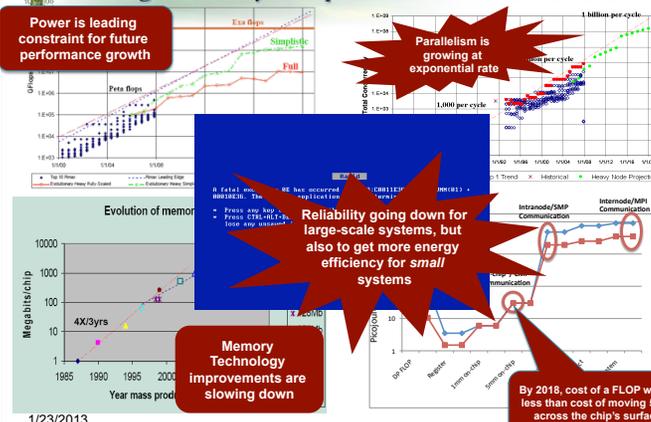
April 2, 2015  
 U.S. DEPARTMENT OF **ENERGY** Office of Science

### Technology Challenges

#### Creating Extremely Complex Machine Architectures

Power is leading constraint for future performance growth

Parallelism is growing at exponential rate



Reliability going down for large-scale systems, but also to get more energy efficiency for small systems

Memory Technology improvements are slowing down

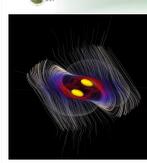
By 2018, cost of a FLOP will be less than cost of moving 5mm across the chip's surface (locality will really matter)

1/23/2013

### Application Code Complexity

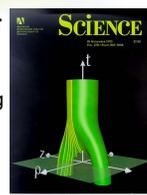
- **Application Complexity has Grown**
  - Big Science on leading-edge HPC systems is a multi-disciplinary, multi-institutional, multi-national efforts! *(and we are not just talking about particle accelerators and Tokamaks)*
  - Looking more like science on atom-smashers
- **Advanced Parallel Languages are Necessary, but NOT Sufficient!**
  - Need higher-level organizing constructs for teams of programmers
  - Languages must work together with frameworks for a complete solution!

### Example: Grand Challenge Simulation Science



**NASA Neutron Star Grand Challenge**

- 5 US Institutions
- Towards colliding neutron stars



**NSF Black Hole Grand Challenge**

- 8 US Institutions, 5 years
- Towards colliding black holes



**Gamma Ray Busts**

**Core Collapse Supernova**

- 10 Inst x 10 years
- *Multiple disciplines*
  - GR
  - Hydro
  - Chemistry
  - Radiation Transp
  - Analytic Topology

**Examples of Future of Science & Engineering**

- *Require Large Scale Simulations, at edge of largest computing sys*
- *Complex multi-physics codes with millions of lines of codes*
- *Require Large Geo-Distributed Cross-Disciplinary Collaborations*

## Community Codes & Frameworks

*(hiding complexity using good SW engineering)*

- **Frameworks (eg. Chombo, Cactus, SIERRA, UPIC, etc...)**
  - Clearly separate roles and responsibilities of your expert programmers from that of the domain experts/scientist/users (productivity layer vs. performance layer)
  - Define a *social contract* between the expert programmers and the domain scientists
  - Enforces software engineering style/discipline to ensure correctness
  - Hides complex domain-specific parallel abstractions from scientist/users to enable performance (hence, most effective when applied to community codes)
  - Allow scientist/users to code nominally serial plug-ins that are invoked by a parallel "driver" (either as DAG or constraint-based scheduler) to enable productivity
- **Properties of the "plug-ins" for successful frameworks (SIAM CSE07)**
  - Relinquish control of main(): invoke user module when framework thinks it is best
  - Module must be stateless (or benefits from that)
  - Module only operates on the data it is handed (well-understood side-effects)
- **Frameworks can be thought of as driver for coarse-grained functional-style of programming**
  - Very much like classic static dataflow, except coarse-grained objects written in declarative language (dataflow without the functional languages)
  - Broad flexibility to schedule Directed Graph of dataflow constraints

## Framework vs. Libraries

- **Library**
  - User program invokes library (*imperative execution model offers limited scheduling freedom*)
  - User defines presents data layout to library (*compiler and system has limited freedom to reorganize to match physical topology of underlying system hardware*)
- **Framework**
  - Framework invokes user plug-in (*declarative execution model*)
  - Only operation on data given (*well defined scope for side-effects*)
  - **Functional semantics provide more scheduling freedom**

## Frameworks vs. Libraries

*(Observation by Koushik Sen: view.eecs.berkeley.edu)*

- A parallel program may be composed of **parallel** and **serial** elements
  - Serial code invoking parallel libraries
  - Parallel patterns with serial plug-ins
- Composition may be recursive

**Parallel Dwarf Libraries**

- Dense matrices
- Sparse matrices
- Spectral
- Combinational
- (Un) Structured Grid

**Parallel Patterns/Frameworks**

- Map Reduce
- Graph traversal
- Dynamic programming
- Backtracking/B&B
- Graphical models
- N-Body
- (Un) Structured Grid

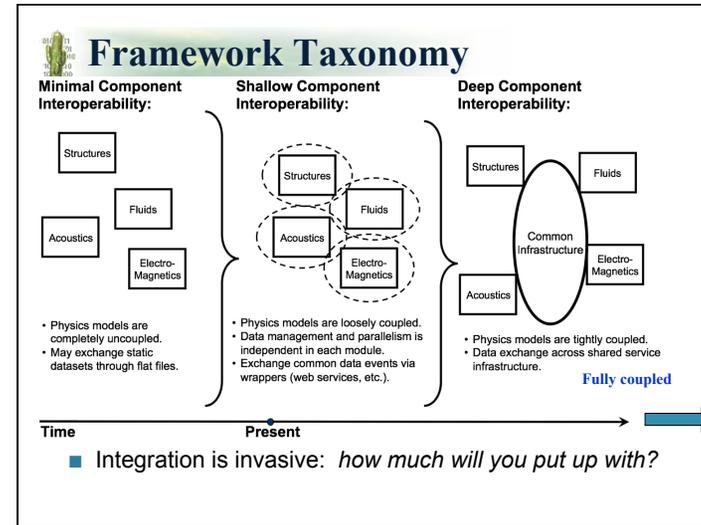
## Separation of Concerns

### Segmented Developer Roles

Developer Roles	Domain Expertise	CS/Coding Expertise	Hardware Expertise
<b>Application:</b> Assemble solver modules to solve science problems. (eg. combine hydro+GR +elliptic solver w/MPI driver for Neutron Star simulation)	Einstein	Elvis	Mort
<b>Solver:</b> Write solver modules to implement algorithms. Solvers use driver layer to implement "idiom for parallelism". (e.g. an elliptic solver or hydrodynamics solver)	Elvis	Einstein	Elvis
<b>Driver:</b> Write low-level data allocation/placement, communication and scheduling to implement "idiom for parallelism" for a given "dwarf". (e.g. PUGH)	Mort	Elvis	Einstein

### Separation of Concerns Segmented Developer Roles

Developer Roles	Conceptual Model	Instantiation
<b>Application:</b> Assemble solver modules to solve science problems.	Neutron Star Simulation: Hydrodynamics + GR Solver using Adaptive Mesh Refinement (AMR)	BSSN GR Solver + MoL integrator + Valencia Hydro + Carpet AMR Driver + Parameter file (params for NS)
<b>Solver:</b> Write solver modules to implement algorithms. Solvers use driver layer to implement "idiom for parallelism".	Elliptic Solver	PETSC Elliptic Solver pkg. (in C) BAM Elliptic Solver (in C++ & F90) John Town's custom BiCG-Stab implementation (in F77)
<b>Driver:</b> Write low-level data allocation/placement, communication and scheduling to implement "idiom for parallelism" for a given "dwarf".	Parallel boundary exchange idiom for structured grid applications	Carpet AMR Driver SAMRAI AMR Driver GrACE AMR driver PUGH (MPI unigrid driver) SHMUGH (SMP unigrid driver)



- ### Observations on Domain-Specific Frameworks
- **Frameworks and domain-specific languages**
    - enforce coding conventions for big software teams
    - Encapsulate a domain-specific "idiom for parallelism"
    - Create familiar semantics for domain experts (more productive)
    - *Clear separation of concerns (separate implementation from specification)*
  - **Common design principles for frameworks from SIAM CSE07 and DARPA Ogdan frameworks meeting**
    - Give up main(): *schedule controlled by framework*
    - Stateless: *Plug-ins only operate on state passed-in when invoked*
    - Bounded (or well-understood) side-effects: *Plug-ins promise to restrict memory touched to that passed to it (same as CILK)*

- ### Benefits and Organizing Principles
- **Other "frameworks" that use same organizing principles (and similar motivation)**
    - NEURON (parallel implementation of Genesis neurodyn)
    - SIERRA (finite elements/structural mechanics)
    - UPIC and TechX (generalized code frameworks for PIC codes)
    - Chombo: AMR on block-structured grids (its hard)
    - Common feature is that computational model is well understood and broadly used (seems to be a good feature for workhorse "languages")
  - **Common benefits (and motivations) are**
    - Modularity (composition using higher-level semantics)
    - Segmenting expertise / Separation of Concerns
    - Unit Testing: This was the biggest benefit
    - Performance analysis (with data aggregated on reasonable semantic boundaries)
    - Correctness testing (on reasonable semantic boundaries)
    - Enables reuse of "solver" components. Replace "driver" if you have a different hardware platform.



## Benefits cont.

### Enabling Collaborative Development!

- **They enable computer scientists and computational scientists to play nicely together**
  - No more arguments about C++ vs. Fortran
  - Easy **unit-testing** to reduce finger pointing (are the CS weenies "tainting the numerics") (also good to accelerate V&V)
  - Enables multidisciplinary collaboration (domain scientists + computer jocks) to enable features that would not otherwise emerge in their own codes!
    - *Scientists write code that seem to never use "new" features*
    - *Computer jocks write code that no reasonable scientist would use*
- **Advanced CS Features are trivially accessible by Application Scientists**
  - Just list the name of the module and it is available
  - Also trivially unit-testable to make sure they don't change numerics
- **Also enables sharing of physics modules among computational scientists**
  - The hardest part is agreeing upon physics interfaces (there is no magic!)
  - *Nice, but not actually not as important as the other benefits (organizing large teams of programmers along the lines of their expertise is the*



## Location of Some Key Frameworks

- **Cactus:** PDEs on Block Structured Grids
  - <http://www.cactuscode.org/>
- **PETSc:** Linear System Solvers
  - <http://www.mcs.anl.gov/petsc/>
- **Chombo:** Adaptive Mesh Refinement
  - <https://commons.lbl.gov/display/chombo/Chombo+Download+Page>
- **Trilinos:** Linear Algebra and Eigensolvers
  - <http://trilinos.org>

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## Examples: CACTUS



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[www.CactusCode.org](http://www.CactusCode.org) Office of  
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## Cactus

- Framework for HPC: code development, simulation control, visualisation
- Manage increased complexity with higher level abstractions, e.g. for inter-node communication, intra-node parallelisation
- Active user community, 10+ years old
  - » Many of these slides are almost 10 years old!
- Supports collaborative development
- Is this a language or just structured programming? (Why is it important to answer this question?)

## Detecting Gravitational Waves

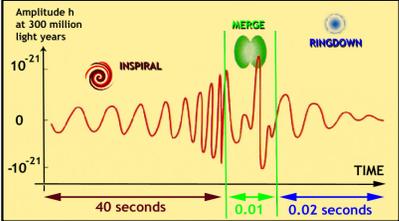
*Will uncover fundamentally new information about the universe*



- LIGO, VIRGO (Pisa), GEO600,... \$1 Billion Worldwide
- Was Einstein right? 5-10 years, we'll see!



**Hanford Washington Site**

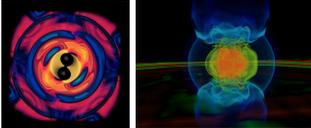


GR requires solution of dozens of coupled, nonlinear hyperbolic-elliptic equations with 1000's of terms (barely have the capability to solve after a century of development)

- Detect GR Waves...pattern matching against numerical templates to enhance signal/noise ratio
- Understand them...just what are the waves telling us?

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## Cactus User Community

- **General Relativity: worldwide usage**
  - LSU(USA), AEI(Germany), UNAM (Mexico), Tuebingen(Germany), Southampton (UK), Sissa(Italy), Valencia (Spain), University of Thessaloniki (Greece), MPA (Germany), RIKEN (Japan), TAT(Denmark), Penn State (USA), University of Texas at Austin (USA), University of Texas at Brwosville (USA), WashU (USA), University of Pittsburgh (USA), University of Arizona (USA), Washburn (USA), UIB (Spain), University of Maryland (USA), Monash (Australia)
- **Astrophysics**
  - Zeus-MP MHD ported to Cactus (Mike Norman: NCSA/UCSD)
- **Computational Fluid Dynamics**
  - KISTI
  - DLR: (turbine design)
- **Chemistry**
  - University of Oklahoma: (Chem reaction vessels)
- **Bioinformatics**
  - Chicago

## Cactus Features

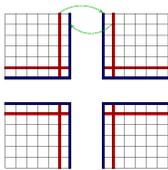
- **Scalable Model of Computation**
  - Cactus provides 'idiom' for parallelism
    - Idiom for Cactus is parallel boundary exchange for block structured grids
    - Algorithm developers provide nominally "serial" plug-ins
    - Algorithm developers are shielded from complexity of parallel implementation
  - Neuron uses similar approach for scalable parallel idiom
- **Build System**
  - User does not see makefiles (*just provides a list of source files in a given module*)
  - "known architectures" used to store accumulated wisdom for multi-platform builds
  - Write once and run everywhere (laptop, desktop, clusters, petaflop HPC)
- **Modular Application Composition System**
  - This is a system for composing algorithm and service components together into a complex composite application
  - Just provide a list of "modules" and they self-organize according to constraints (*less tedious than explicit workflow*)
  - Enables unit testing for V&V of complex multiphysics applications
- **Language Neutrality**
  - Write modules in any language (*C, C++, F77, F90, Java, etc...*)
  - Automatically generates bindings (also hidden from user)
  - Overcomes age-old religious battles about programming languages

## Cactus components (terminology)

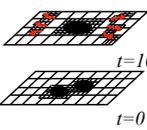
- **Thorns (modules):**
  - Source Code
  - CCL: Cactus Configuration Language (Cactus C&C description)
    - Interface/Types: polymorphic datastructures instantiated in "driver-independent" manner
    - Schedule: constraints-based schedule
    - Parameter: must declare free parameters in common way for introspection, steering, GUIs, and common input parameter parser.
- **Driver:** Separates implementation of parallelism from implementation of the "solver" (can have Driver for MPI, or threads, or CUDA)
  - Instantiation of the parallel datastructures (control of the domain-decomposition)
  - Handles scheduling and implementation of parallelism (threads or whatever)
  - Implements communication abstraction
  - Drive must own all of these
- **Flesh:** Glues everything together
  - Just provide a "list" of modules and they self-assemble based on their constraints expressed by CCL
  - CCL not really a language

## Idiom for Parallelism in Cactus

- **The central idiom for the Cactus model of computation is boundary exchange**
  - Cactus is designed around a distributed memory model.
  - Each module (algorithm plug-in) is passed a section of the global grid.
- **The actual parallel driver (implemented in a module)**
  - Driver decides how to decompose grid across processors and exchange ghost zone information
  - Each module is presented with a standard interface, independent of the driver
  - Can completely change the driver for shared memory, multicore, message passing without requiring any change of the physics modules
- **Standard driver distributed with Cactus (PUGH) is for a parallel unigrid and uses MPI for the communication layer**
- **PUGH can do custom processor decomposition and static load balancing**
- **Same idiom also works for AMR and unstructured grids!!! (no changes to solver code when switching drivers)**
  - Carpet (Erik Schnetter's AMR driver)
  - DAGH/GrACE driver for Cactus
  - SAMRAI driver for Cactus



Unigrid



AMR





## How Does Cactus Work?

### Primer on PDE Solvers on Block Structured Grids



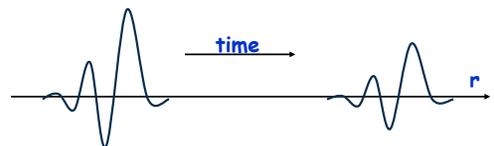
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**Science**



## Scalar Wave Model Problem

Scalar waves in 3D are solutions of the hyperbolic wave equation:  $-\phi_{,tt} + \phi_{,xx} + \phi_{,yy} + \phi_{,zz} = 0$

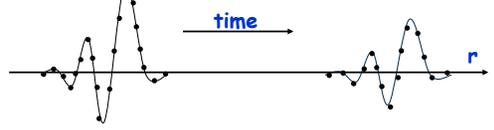
**Initial value problem:** given data for  $\phi$  and its first time derivative at initial time, the wave equation says how it evolves with time



## Numerical Method

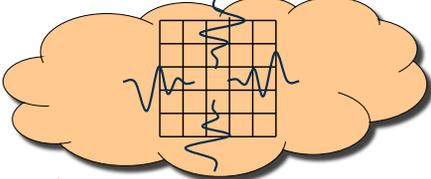
Numerical solve by discretising on a grid, using explicit *finite differencing* (centered, second order)

$$\begin{aligned} \phi^{n+1}_{i,j,k} = & 2\phi^n_{i,j,k} - \phi^{n-1}_{i,j,k} \\ & + \Delta t^2/\Delta x^2(\phi^n_{i+1,j,k} - 2\phi^n_{i,j,k} + \phi^n_{i-1,j,k}) \\ & + \Delta t^2/\Delta y^2(\phi^n_{i,j+1,k} - 2\phi^n_{i,j,k} + \phi^n_{i,j-1,k}) \\ & + \Delta t^2/\Delta z^2(\phi^n_{i,j,k+1} - 2\phi^n_{i,j,k} + \phi^n_{i,j,k-1}) \end{aligned}$$



## Numerical Method

- Finite grid, so need to apply outer boundary conditions



- Main parameters:
  - grid spacings:  $\Delta t$ ,  $\Delta x$ ,  $\Delta y$ ,  $\Delta z$ , which coords?, which initial data?
- Simple problem, analytic solutions, but contains many features needed for modelling more complex problems

## Example Stand Alone Code: Main.f

```

c =====
c program WaveToy
c =====
c Fortran 77 program for 3D wave equation.
c Explicit finite difference method.
c =====

c Global variables in include file
include "WaveToy.h"
integer i,j,k

c SET UP PARAMETERS
nx = 30
[MORE PARAMETERS]

c SET UP COORDINATE SYSTEM AND GRID
x_origin = (0.5 - nx/2)*dx
y_origin = (0.5 - ny/2)*dy
z_origin = (0.5 - nz/2)*dz

do i=1,nx
do j=1,ny
do k=1,nz
x(i,j,k) = dx*(i-1) + x_origin
y(i,j,k) = dy*(j-1) + y_origin
z(i,j,k) = dz*(k-1) + z_origin
r(i,j,k) = sqrt(x(i,j,k)**2+y(i,j,k)**2+z(i,j,k)**2)
end do
end do
end do

c OPEN OUTPUT FILES
open(unit=11,file="out.x")
open(unit=12,file="out.y")
open(unit=13,file="out.z")

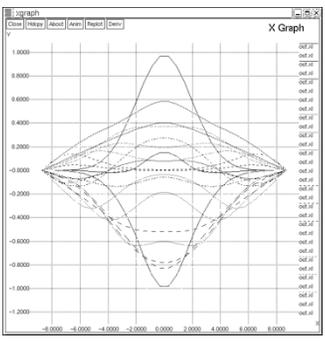
c SET UP INITIAL DATA
call InitialData
call Output

c EVOLVING
do iteration = 1, nt
call Evolve
if (mod(iteration,10).eq.0) call Output
end do

stop
end
    
```

## Standalone Serial Program

Setting up parameters  
 Setting up grid and coordinate system  
 Opening output files  
 Setting up initial data  
 Performing iteration 10  
 Performing iteration 20  
 Performing iteration 30  
 Performing iteration 40  
 Performing iteration 50  
 Performing iteration 60  
 Performing iteration 70  
 Performing iteration 80  
 Performing iteration 90  
 Performing iteration 100  
 Done



## Making a "Thorn" (a Cactus Module)

```

=====
program WaveToy
=====
Fortran 77 program for 3D wave equation
Explicit finite difference method.
=====

Global variables in include file
include "WaveToy.h"
integer i,j,k

SET UP PARAMETERS
nx = 30
[MORE PARAMETERS]

SET UP COORDINATE SYSTEM AND GRID
x_origin = (0.5 - nx/2)*dx
y_origin = (0.5 - ny/2)*dy
z_origin = (0.5 - nz/2)*dz

do i=1,nx
do j=1,ny
do k=1,nz
x(i,j,k) = dx*(i-1) + x_origin
y(i,j,k) = dy*(j-1) + y_origin
z(i,j,k) = dz*(k-1) + z_origin
r(i,j,k) = sqrt(x(i,j,k)**2+y(i,j,k)**2+z(i,j,k)**2)
end do
end do
end do

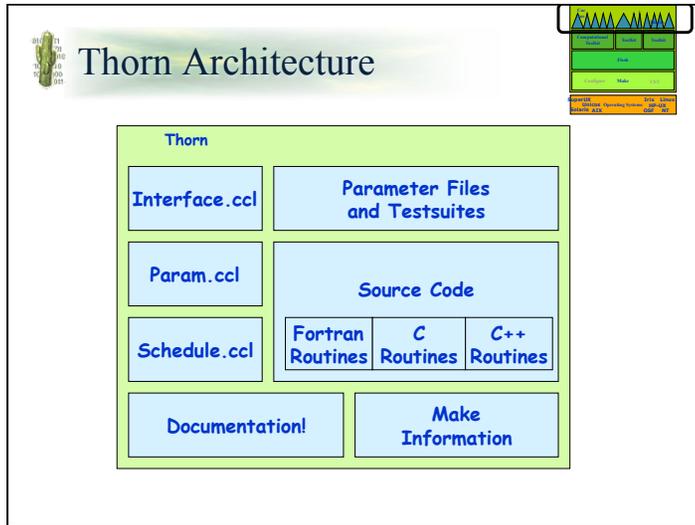
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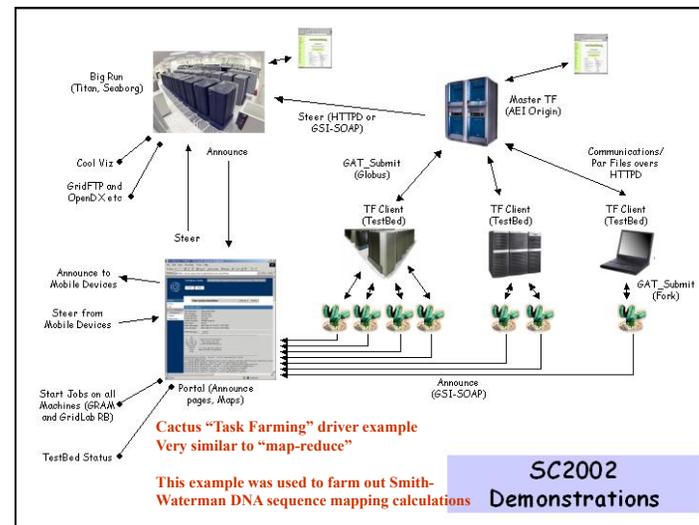
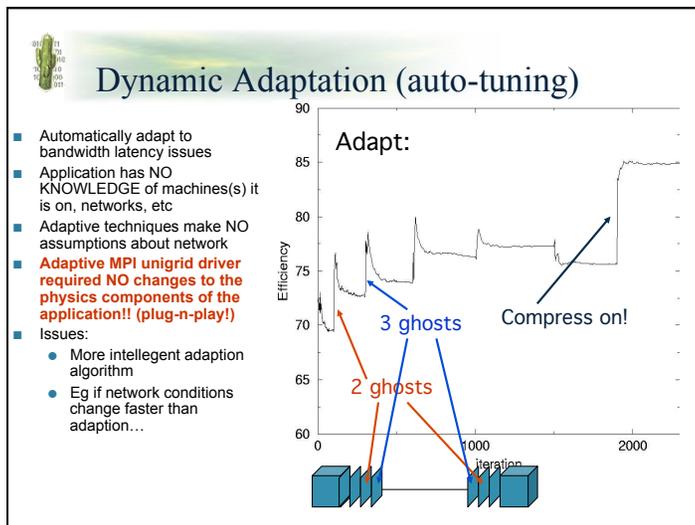
stop
end
    
```

**Throw the rest of this stuff away (less writing) And get parallelism, modularity, and portability for free**



### Abstraction Enables Auto-Tuning

- The following example shows how the framework abstractions enable auto-tuning of the parallel performance of a code without any change to the higher-levels of the framework
  - Normally people accuse abstractions of reducing performance
  - Framework abstractions \*enable\* performance tuning!!!



## Fault Tolerance

- Need checkpointing/recovery on steroids, need to cope with partial failure
- Checkpoint is transparent to application (*uses introspection*) -architecture independent (independent of system HW and SW)
- Able to change number of active nodes
- Example: keep log of inter-processor messages, so that a lost node can be replaced
- Contain failure, continue simulation

Regular checkpointing

"Localized" checkpointing

time ↑

## Nomadic Application Codes

(Foster, Angulo, Cactus Team...)

Running At UC      Load applied      3 successive Resource contract violations & migration      Running At UIUC

Iterations/Second

Clock Time

## Hybrid Communication Models

- New "multicore" driver required no changes to physics components!
- Use MPI between nodes, OpenMP within nodes

Einstein Equations (Abe, NCSA)

- Common address space enables more cache optimisations
- Cactus framework offers abstraction layer for parallelisation: basic OpenMP features work as black box (*central idiom*)

## Remote Monitoring/Steering: Thorn HTTPD and SMS Messaging

- Thorn which allows simulation any to act as its own web server
- Connect to simulation from any browser anywhere ... collaborate
- Monitor run: parameters, basic visualization, ...
- Change *steerable* parameters
- See running example at [www.CactusCode.org](http://www.CactusCode.org)
- Get Text Messages from your simulation or chat with it on IM!

## Remote Visualization

OpenDX

LCAVision

Amira

Visapuit

Source Volume

xgraph

IsoView

gnuplot

[www.cactuscode.org/VizTools](http://www.cactuscode.org/VizTools)

## Another Framework Example

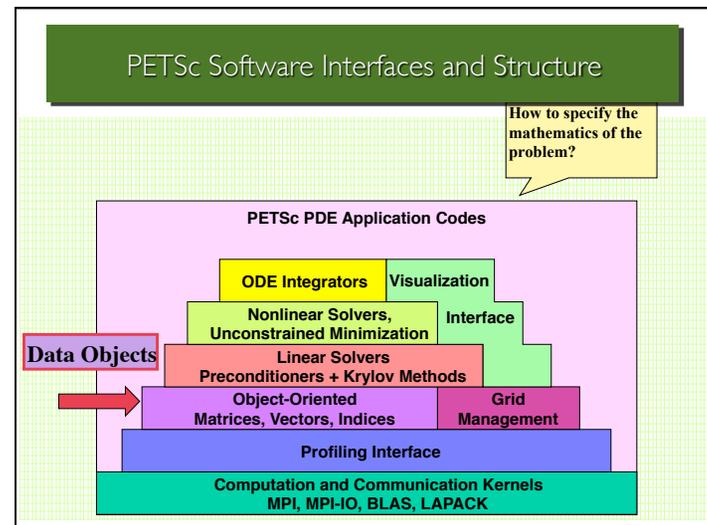
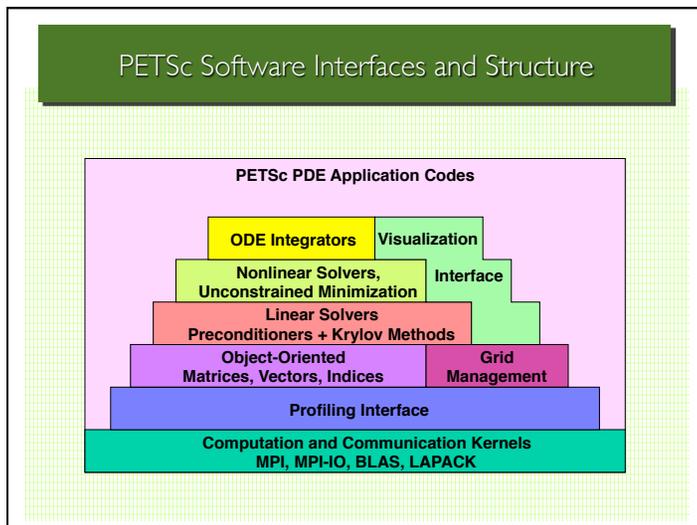
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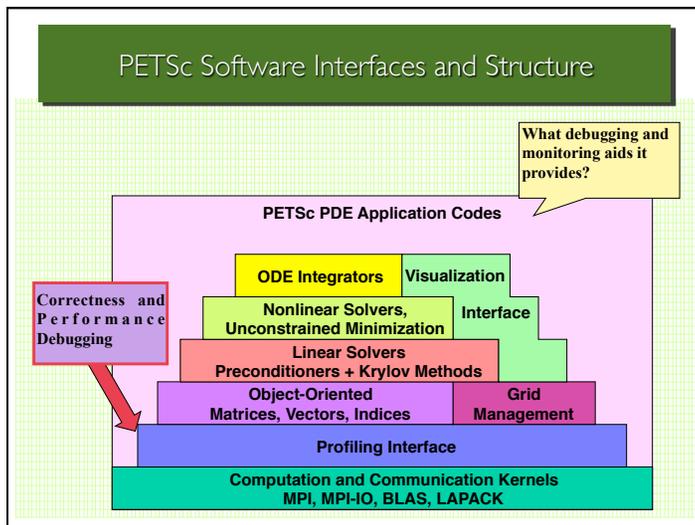
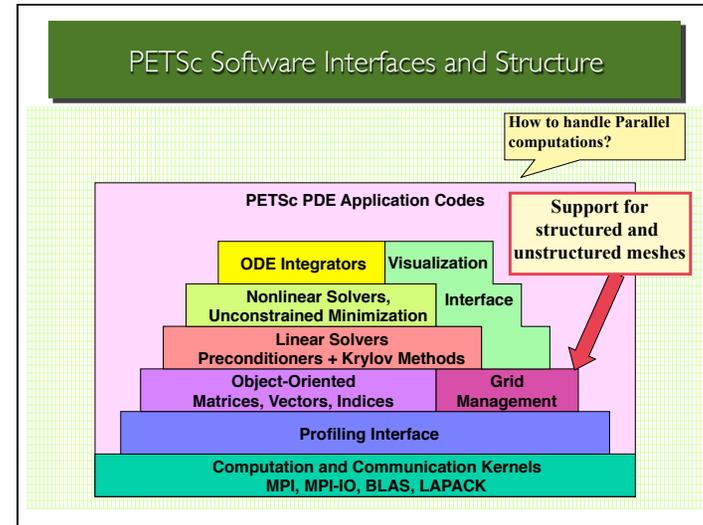
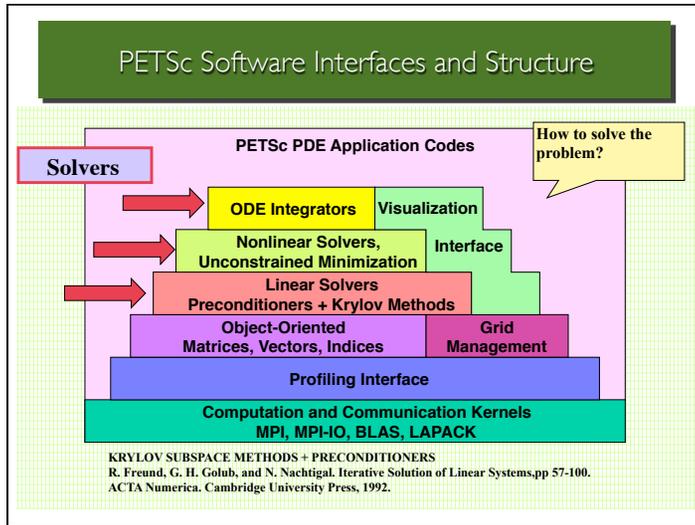
### PETSc

Slides from: Barry Smith, Jed Brown, Karl Rupp,  
Matthew Knepley

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### Some Algorithmic Implementations in PETSc

Nonlinear Solvers			Time Steppers			
Newton-based Methods	Other		Euler	Backward Euler	Pseudo Time Stepping	Other
Line Search	Trust Region					
Krylov Subspace Methods						
GMRES	CG	CGS	Bi-CG-STAB	TFQMR	Richardson	Chebyshev Other
Preconditioners						
Additive Schwarz	Block Jacobi	Jacobi	ILU	ICC	LU (Sequential only)	Others
Matrices						
Compressed Sparse Row (AJ)	Blocked Compressed Sparse Row (BAJ)	Block Diagonal (BDIAG)	Dense	Matrix-free	Other	
Distributed Arrays			Index Sets			
Vectors			Indices	Block Indices	Stride	Other

### Basic Program setup in PETSc ( C/C++ )

```

#include "petsc.h"
int main( int argc, char *argv[] )
{
    PetscInitialize(&argc,&argv);
    • PetscPrintf(PETSC_COMM_WORLD,"Hello World\n");
    • PetscFinalize();
    return 0;
}
    
```

### Basic Program Setup in PETSc (Fortran)

```

• program main
• integer ierr, rank
#include "include/finclude/petsc.h"
• call PetscInitialize( PETSC_NULL_CHARACTER, ierr )
• call MPI_Comm_rank( PETSC_COMM_WORLD, rank, ierr )
• if (rank .eq. 0) then
    print *, 'Hello World'
• endif
• call PetscFinalize(ierr)
• end
    
```

### Vectors and Matrices in PETSc

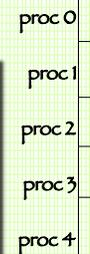
**VECTORS**  
 Fundamental objects to store fields, right-hand side vectors, solution vectors, etc. . .

**Matrices**  
 Fundamental Objects to store Operators

### PETSC: Some Basic Vector Operations

• PETSc vectors can be sequential (full vector is created in every process) or parallel (every process contains a part of the vector)

- Create a PETSc Vector  
 VecCreate(MPI\_Comm Comm, Vec \* v)  
 • comm - MPI\_Comm parallel processes  
 • v = vector
- Set the PETSc Vector type:  
 VecSetType(Vec, VecType)  
 • Vector Types can be:  
 - VEC\_SEQ, VEC\_MPI, or VEC\_SHARED
- Set the PETSc vector size:  
 VecSetSizes(Vec \*v, int n, int N)  
 • Where n or N (not both) could be PETSC\_DECIDE
- Destroy a PETSc Vector (Important for storage)  
 VecDestroy(Vec \*)



## PETSC: Some Basic Vector Operations

```
#include petscvec.h
int main(int argc, char **argv)
{
    Vec      x;
    int      n = 20, m=4, ierr;
    VecCreateMPI(PETSC_COMM_WORLD, m, n, x);
    // .....
    VecSetFromOptions(x);
    <-- perform some vector operations -->

    PetscFinalize();
    return 0;
}
```

Or to create a specific MPI vector

## PETSC: Some Basic Vector Operations

Function Name	Operation
VecAXPY(Scalar *a, Vec x, Vec y)	$y = y + a*x$
VecAYPX(Scalar *a, Vec x, Vec y)	$y = x + a*y$
VecWAXPY(Scalar *a, Vec x, Vec y, Vec w)	$w = a*x + y$
VecScale(Scalar *a, Vec x)	$x = a*x$
VecCopy(Vec x, Vec y)	$y = x$
VecPointwiseMult(Vec x, Vec y, Vec w)	$w_i = x_i * y_i$
VecMax(Vec x, int *idx, double *r)	$r = \max x_i$
VecShift(Scalar *s, Vec x)	$x_i = s + x_i$
VecAbs(Vec x)	$x_i =  x_i $
VecNorm(Vec x, NormType type, double *r)	$r = \ x\ $

## PETSC: Some Basic Matrix Operations

- Create a PETSc Matrix  
MatCreate(MPI\_Comm comm, Mat \*A)
- Set the PETSc Matrix type  
MatSetType(Mat \*A, MatType matype)  
(see next slides for types of matrices)
- Set the PETSc Matrix sizes  
MatSetSizes(Mat \*A, PetscInt m, PetscInt n, PetscInt M, PetscInt N)
  - where m, n are the dimensions of local sub-matrix. M, N are the dimensions of the global matrix A
- Destroy a PETSc Matrix  
MatDestroy(Mat \*A)

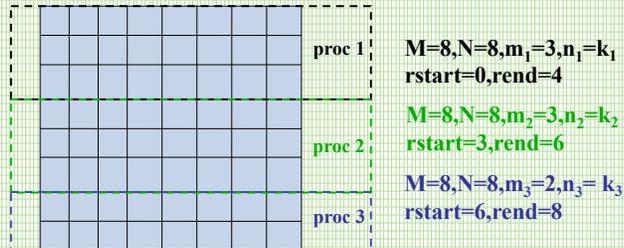
## PETSC: Some Basic Matrix Operations

### PETSc Matrix Types:

- default sparse AIJ (generic), MPIAIJ (parallel), SEQAIJ (sequential)
- block sparse AIJ (for multi-component PDEs): MPIAIJ, SEQAIJ
- symmetric block sparse AIJ: MPISBAIJ, SAEQSBIAIJ
- block diagonal: MPIBIDIAG, SEQBIDIAG
- dense: MPIDENSE, SEQDENSE
- matrix-free
- many more formats (check documentation)

## PETSC: Some Basic Vector Operations

Every process will receive a set of consecutive and non-overlapping rows, the columns are determined by the matrix non-zero structure ( $\max(n_i) = N$ )



## PETSC: Some Basic Matrix Operations

### - Input values to the matrix

In PETSc a process can input values for blocks of the matrix that are not in its local matrix. PETSc makes sure these values get to the right places and corresponding processes.

```
MatSetValues(Mat mat,
             PetscInt m, PetscInt idxm[],
             PetscInt n, PetscInt idxn[],
             PetscScalar v[], InsertMode addv)
```

- `idxm` is a vector of global row indices and `m` is the number of rows in `idxm`
- `idxn` is a vector of global column indices and `n` is the number of columns in `idxn`
- `v` is an array of  $m \times n$  values
- `addv` is either `ADD_VALUES` (accumulates) or `INSERT_VALUES` (sets)

## PETSC: Some Basic Matrix Operations

### - Assembling the parallel matrix

(must do before calling solvers and other operations!)

```
MatAssemblyBegin(Mat mat, MatAssemblyType type)
```

**MatAssemblyType:**

- `MAT_FLUSH_ASSEMBLY` use between `ADD_VALUES` and `INSERT_VALUES` in `MatSetValues`
- `MAT_FINAL_ASSEMBLY` use after setting all the values in the matrix and before the matrix is used in the code

```
MatAssemblyEnd(Mat mat, MatAssemblyType type)
```

## PETSC: Some Basic Matrix Operations

### - Matrix vector multiplication

```
MatMult(Mat A, Vec y, Vec x) (y=x)
```

### - Matrix viewing

```
MatView(Mat mat, PetscViewer viewer)
```

#### • PetscViewer some viewer options:

- `PETSC_VIEWER_STDOUT_SELF` standard output (default)
- `PETSC_VIEWER_STDOUT_WORLD` synchronized standard output, only rank 0 prints - others send to rank 0
- `PETSC_VIEWER_DRAW_WORLD` graphical display of nonzero structure

### PETSc: Some Basic Viewer Operations

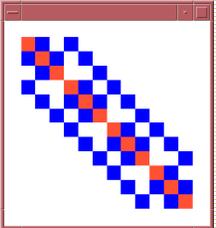
- VIEWERS provide information on any PETSc conceptual Object
- VIEWERS can be setup inside the program or at execution time
- VIEWERS provide an interface for extracting data and making it available to other tools and libraries
  - vector fields, matrix contents
  - various formats (ASCII, binary)
- Visualization
  - simple graphics created with X11.

### PETSc: Some Basic Viewer Operations

```
MatView(Mat A, PetscViewer v);
```

With `PETSC_VIEWER_DRAW_WORLD`

- Other useful viewers can be set through `PETScViewerSetFormat`:
  - `PETSC_VIEWER_ASCII_MATLAB`
  - `PETSC_VIEWER_ASCII_DENSE`
  - `PETSC_VIEWER_ASCII_INFO`
  - `PETSC_VIEWER_ASCII_INFO_DETAILED`



### PETSc: Some Vector, Viewer and Matrix Examples

Included in the PETSc Distribution:

- 1) `$PETSC_DIR/src/mat/tests/ex2.c`
- 2) Use of `-mat_view_info_detailed`, etc
- 3) `$PETSC_DIR/src/mat/tests/ex3.c`
- 4) Use of `-mat-view-draw`

### Linear Systems in PETSc

- PETSc Linear System Solver Interface (KSP)
- Solve:  $Ax=b$ ,
- Based on the Krylov subspace methods with the use of a preconditioning technique to accelerate the convergence rate of the numerical scheme.

**KRYLOV SUBSPACE METHODS + PRECONDITIONERS**  
 R. Freund, G. H. Golub, and N. Nachtigal. *Iterative Solution of Linear Systems*, pp 57-100. ACTA Numerica. Cambridge University Press, 1992.

- For left and right preconditioning matrices,  $M_L$  and  $M_R$ , respectively
 
$$(M_L^{-1} A M_R^{-1}) (M_R x) = M_L^{-1} b$$

For  $M_R = I$

$r_L = M_L^{-1} b - M_L^{-1} A x = M_L^{-1} r$

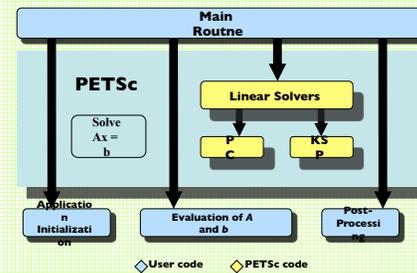
PETSc Default

## Linear Systems in PETSc

- . To solve a Linear System,  $Ax = b$  in PETSc, one needs:
- . Declare  $x$ ,  $b$  as PETSc vectors, and set the RHS  $b$
- . Declare the matrix  $A$ , and explicitly set the matrix  $A$  when appropriate
- . Set the Solver KSP:
  - . Option 1:
    - . Select the base Krylov subspace based solver
    - . Select the preconditioner (PETSc PC)
  - . Option 2:
    - . Set the solver to use a solver from an external library

## Linear Systems in PETSc

Schema of the program control flow



## PETSc: Linear Solver - KSP Interface

### KSP Object:

- Is the key element to manipulate linear solver
- Stores the state of the solver and other relevant information like:
  - Convergence rate and tolerance
  - Number of iteration steps
  - Preconditioners

## PETSc: Linear Solver - KSP Interface

- Create a KSP Object  
`KSPCreate(MPI_Comm comm, KSP *ksp)`
- Set KSP Operators  
`KSPSetOperators(KSP *ksp, Mat Amat, Mat Pmat, MatStructure flag)`

Amat: is the original matrix from  $Ax=b$

Pmat: is the place holder for the preconditioning matrix (can be the same as A)

flag: saves work while repeatedly solving linear systems of the same size using the same preconditioners. Possible values:

`SAME_NONZERO_PATTERN` (same pattern for Pmat)  
`DIFFERENT_NONZERO_PATTERN` (different pattern for Pmat)  
`SAM_PRECONDITIONER` (identical Pmat)

### PETSc: Linear Solver - KSP Interface

- Solve Linear System  
`KSPSolve(KSP *ksp, Vec b, Vec x)`
- Get Iteration Number  
`KSPSolve(KSP *ksp, int *its)`
- Destroy Solver  
`KSPDestroy(KSP *ksp)`

### PETSc: Linear Solver - KSP Interface

- Set the type PETSc KSP solver  
`KSPSetType(KSP *ksp, KSPType method)`

Method	KSPType	Options Database Name	Default Convergence Monitor <sup>†</sup>
Richardson	KSPRICHARDSON	richardson	true
Chebyshev	KSPCHEBYCHEV	chebychev	true
Conjugate Gradient [11]	KSPCG	cg	true
BiConjugate Gradient	KSPBICG	bicg	true
Generalized Minimal Residual [15]	KSPGMRES	gmres	precond
BICGSTAB [18]	KSPBCGS	bcgs	precond
Conjugate Gradient Squared [17]	KSPCGS	cgs	precond
Transpose-Free Quasi-Minimal Residual (1) [7]	KSPTFQMR	tfqmr	precond
Transpose-Free Quasi-Minimal Residual (2)	KSPTCQMR	tcqmr	precond
Conjugate Residual	KSPCR	cr	precond
Least Squares Method	KSPLSQR	lsqr	precond
Shell for no KSP method	KSPPREONLY	preonly	precond

<sup>†</sup>true - denotes true residual norm, precondition - denotes preconditioned residual norm

Table 3: KSP Defaults. All methods use left preconditioning by default.

### PETSc: Linear Solver - KSP Interface

- Some useful command line parameters to PETSc (run time!)
 

- `-ksp_type [cg, gmres, bcgs, tfqmr, ...]`
  - `-pc_type [lu, ilu, jacobi, sor, asm, ...]`

More advanced options:

  - `-ksp_max_it <max_iters>`
  - `-ksp_gmres_restart <restart>`
  - `-pc_asm_overlap <overlap>`
  - `-pc_asm_type [basic, restrict, interpolate, none]`
  - Many more, use `-help` to see other options

### PETSc: Linear Solver - KSP Interface

- Setting up the Preconditioners  
`KSPGetPC(KSP ksp, PC *pc);`  
`PCSetType(PC *pc, const PCType type)`

Method	PCType	Options Database Name
Jacobi	PCJACOBI	jacobi
Block Jacobi	PCBJACOBI	bjacobi
SOR (and SSOR)	PCSOR	sor
SOR with Eisenstat trick	PCEISENSTAT	eisenstat
Incomplete Cholesky	PCICC	icc
Incomplete LU	PCILU	ilu
Additive Schwarz	PCASM	asm
Linear solver	PCKSP	ksp
Combination of preconditioners	PCCOMPOSITE	composite
LU	PCLU	lu
Cholesky	PCCholesky	cholesky
No preconditioning	PCNONE	none
Shell for user-defined PC	PCSHELL	shell

Table 4: PETSc Preconditioners

## PETSc: Linear Solver - KSP Interoperable Interface

**Use of solvers in external libraries**

3. Use the runtime option: `-ksp_type preonly -pc_type <pctype> -pc_factor_mat_solver_package <packagename>`. For eg: `-ksp_type preonly -pc_type lu -pc_factor_mat_solver_package superlu_dist`.

MatType	PCType	MatSolverPackage	Package (-pc_factor_mat_solver_package)
baij	cholesky	MAT_SOLVER_DSCPACK	dscpack
seqaij	lu	MAT_SOLVER_ESSL	essl
seqaij	lu	MAT_SOLVER_LUSOL	lusol
seqaij	lu	MAT_SOLVER_MATLAB	matlab
aij	lu	MAT_SOLVER_MUMPS	mumps
sbaij	cholesky		
plapack	lu	MAT_SOLVER_PLAPACK	plapack
plapack	cholesky		
aij	lu	MAT_SOLVER_SPOOLES	spooles
sbaij	cholesky		
seqaij	lu	MAT_SOLVER_SUPERLU	superlu
aij	lu	MAT_SOLVER_SUPERLU_DIST	superlu_dist
seqaij	lu	MAT_SOLVER_UMFPACK	umfpack

Table 5: Options for External Solvers

## PETSC: Linear Solver Examples

**Included in the PETSc Distribution:**

- 1) `$PETSC_DIR/src/ksp/ksp/examples/tests/ex2.c`
- 2) `$PETSC_DIR/src/ksp/ksp/examples/tests/ex5.c`  
(understand the use of multigrid in PETSc)

## Location of Some Key Frameworks

- **Cactus:** PDEs on Block Structured Grids
  - <http://www.cactuscode.org/>
- **PETSc:** Linear System Solvers
  - <http://www.mcs.anl.gov/petsc/>
- **Chombo:** Adaptive Mesh Refinement
  - <https://commons.lbl.gov/display/chombo/Chombo+Download+Page>
- **Trillinos:** Linear Algebra and Eigensolvers
  - <http://trilinos.org>

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NERSC

Lawrence Berkeley National Laboratory / National Energy Research Supercomputing Center

## More Opportunities for Data Abstractions using Frameworks

Future considerations for framework design

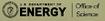
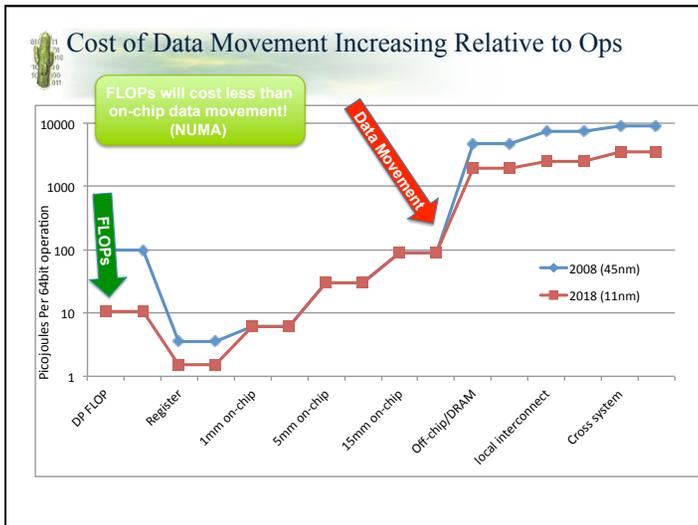
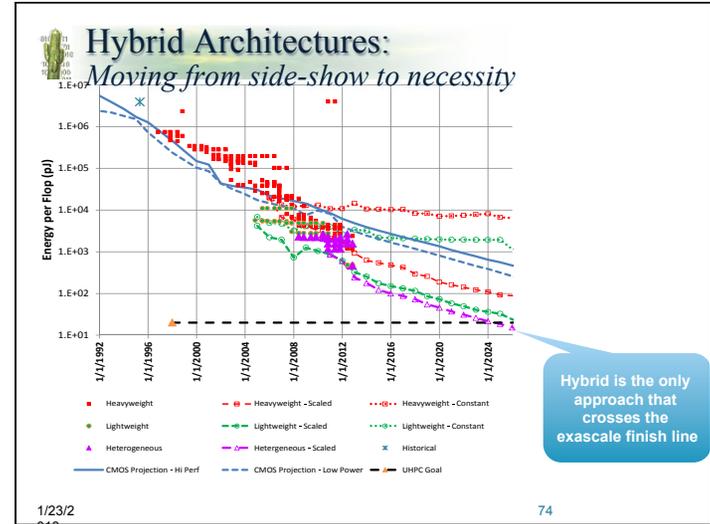
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# Exascale Strawman Arch

Based on input from DOE Fast Forward and Design Forward Projects

- Let's review where things are going in exascale concept designs

## Can Get Capacity OR Bandwidth But Cannot Get Both in the Same Technology

Cost (increases for higher capacity and cost/bit increases with bandwidth)

Bandwidth\Capacity	16 GB	32 GB	64 GB	128 GB	256 GB	512 GB	1 TB
4 TB/s							
2 TB/s	Stack/PNM						
1 TB/s			Interposer				
512 GB/s				HMC organic			
256 GB/s					DIMM		
128 GB/s							NVRAM

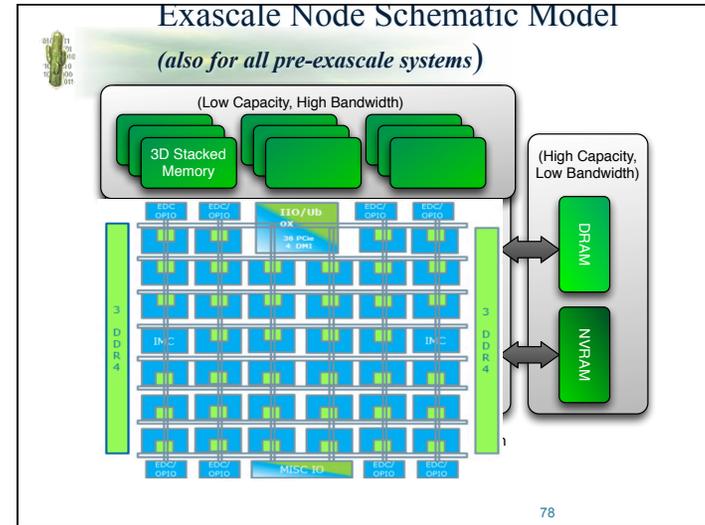
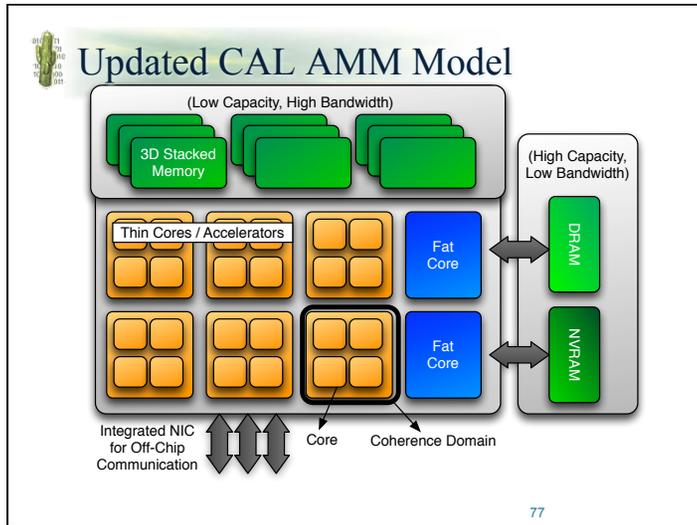
### Old Paradigm

- One kind of memory (JEDEC/DDRx)
- ~1 byte per flop memory capacity
- ~1 byte per flop bandwidth

### New Paradigm

- DDR4: ~1 byte per flop capacity with < 0.01 bytes/flop BW
- Stacked Memory: ~1 byte per flop bandwidth < 0.01 bytes/flop capacity
- NVRAM: More capacity, but consumes more Energy for writes than for reads.

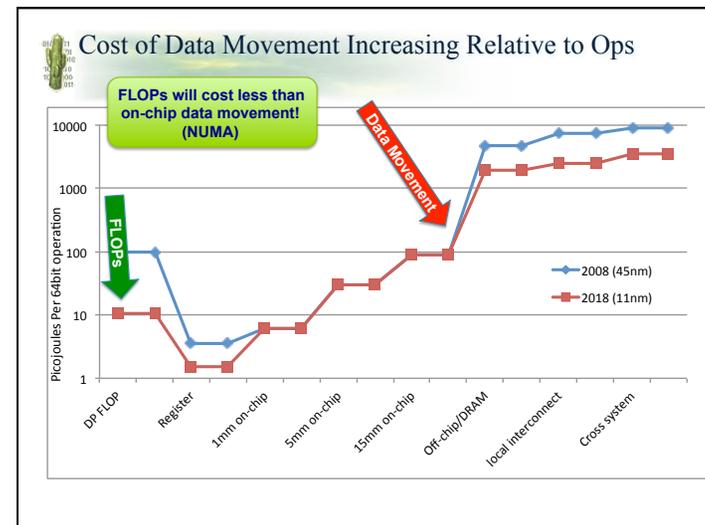
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## Data Locality

What are the big questions in Fast Forward

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### Data-Centric Programming Model

(current compute-centric models are mismatched with emerging hardware)

- Building up a hierarchical layout
  - Layout block coreblk {blockx,blocky};
  - Layout block nodeblk {nnx,nnx,nnz};
  - Layout hierarchy myheirarchy {coreblk,nodeblk};
  - Show

**Data Centric Programming paradigm is also central to "big data" applications.**

```

for (i=0; i<nx; i++) {
  for (j=0; j<ny; j++) {
    for (k=0; k<nz; k++) {
      a[i][j][k]=C*a[i+1]...>
    }
  }
}
    
```

And if layout changes, this loop remains the same

Satisfies the request of the application developers (minimize the amount of code that changes)

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### Tiling Formulation: abstracts data locality, topology, cache coherence, and massive parallelism

- Expose massive degrees of parallelism through domain decomposition
  - Represent an atomic unit of work
  - Task scheduler works on tiles
- Core concept for data locality
  - Vertical data movement
    - Hierarchical partitioning
  - Horizontal data movement
    - Co-locate tiles sharing the same data by respecting tile topology
- Multi-level parallelism
  - Coarse-grain parallelism: across tiles
  - Fine-grain parallelism: vectorization, instruction ordering within tile
- TIDA: Centralize and parameterize tiling information at the data structures
  - Direct approach for memory affinity management for data locality
  - Expose massive degrees of parallelism through domain decomposition
  - Overcomes challenges of relaxed coherency & coherence domains!!!

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### Tiling: Abstraction for Memory Layout

CAF2, UPC++, Chapel, TiDA, Raja/Kokkos

- OpenMP allows a user to specify any of these layouts
- However, the code needed to express that must be different for GPUs vs CPUs.
- The solvers remain unchanged !!!

a) Logical Tiles(CPU)      b) Separated Tiles (GPU)

c) Regional Tiles

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### Iterating over Tiles

```

do tileno=1, ntiles (tiledA)
  Get tile and its range: t1 = get_tile(tiledA, tileno)
                       lo = lwb(t1)
                       hi = upb(t1)
  Get data ptrs:      A => dataptr(tiledA, tileno)
                       B => dataptr(tiledB, tileno)

  do j=lo(2), hi(2)
    do i=lo(1), hi(1)
      Element Loops: B(i,j)= A(i,j) ...
      Loop body remains unchanged
    end do
  end do
end do
    
```

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## Iterating over Tiles

```

do tileno=1, ntiles (tiledA) } Tiling loop
  t1 = get_tile(tiledA, tileno)
    lo = lwb(t1)
    hi = upb(t1)
  A => dataptr(tiledA, tileno)
  B => dataptr(tiledB, tileno)

  do j=lo(2), hi(2) } Element Loops
    do i=lo(1), hi(1)
      B(i,j)= A(i,j) ...
    end do
  end do
end do

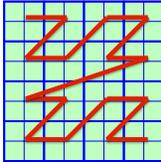
```

There are many ways to iterate over element and tile loops.

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## Loop Traversal

- Iterate over the tiles by preserving data locality
- Provide a language construct to abstract loop traversal
  - Execute a tile in any order or execute elements in a tile in any order
  - Introduce parallelization strategy for tiles and elements



- The new loop construct will
  - Respect data layout and topology when we traverse the loop
    - Morton order, linear order
  - Let compiler and runtime pick the best traversal strategy
  - Change parallelization strategy without changing the loop

Related Work:

- C++ lambda func in Raja
- Functors in Kokkos

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## Library-> Directives->Language

- The prototype for TiDA targets F90 base language**
  - Native support for multidimensional arrays
- Framework**
  - Minimal invasion to the base language and existing codes
    - We can get quite far without implementing a compiler
  - Have to implement the optimization variants by hand
- Directives**
  - Intermediate step, can be ignored, preferred by apps developers
- Language Extension**
  - Changes the type system in a language
  - Provides the compiler more opportunities to perform code transformations
  - Our ultimate goal

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## Tile loops and Element Loops

```

do tileno=1, ntiles (tU)
  t1 = get_tile(tU, tileno)
  lo = lwb(t1)
  hi = upb(t1)
  up => dataptr(tU, tileno)
  dp => dataptr(tD, tileno)

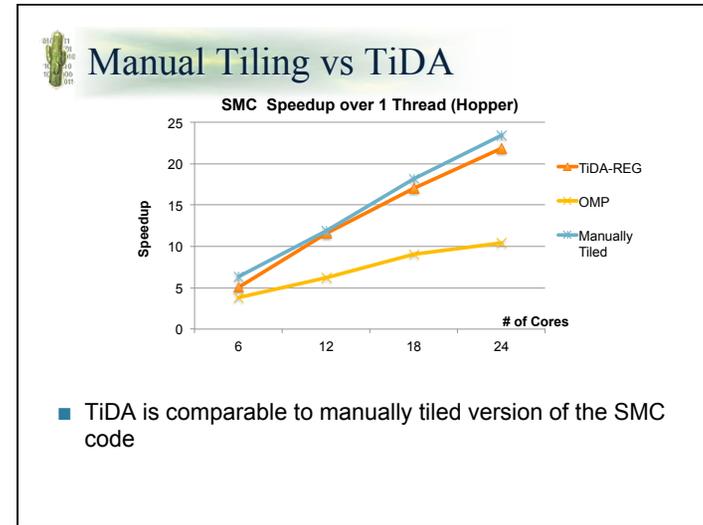
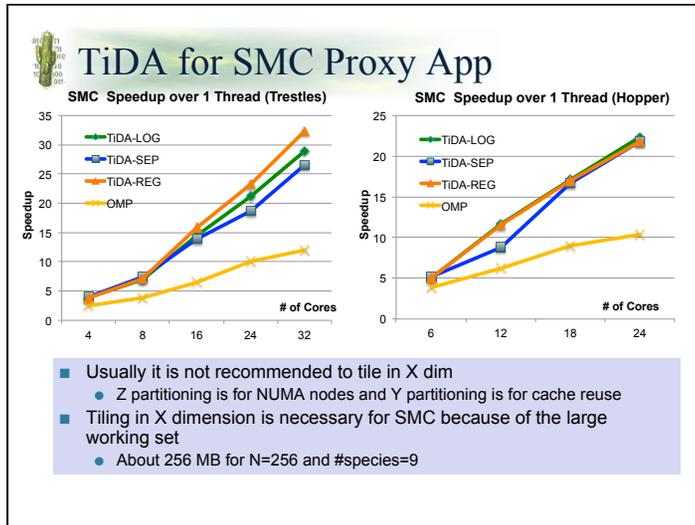
  do j=lo(2), hi(2)
    do i=lo(1), hi(1)
      up(i,j)= dp(i,j) ...
    end do
  end do
end do

```

Iteration Space (C++11 lambda)

This Part would go away if TIDA is a Language Construct

Element Loop(s)



## Heterogeneity / Inhomogeneity Async Programming Models?

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### Assumptions of Uniformity is Breaking

(many new sources of heterogeneity)

- Bulk Synchronous Execution
- Heterogeneous compute engines (hybrid/GPU computing)
  - Fine grained power mgmt. makes homogeneous cores look heterogeneous
    - thermal throttling – no longer guarantee deterministic clock rate
  - Nonuniformities in process technology creates non-uniform operating characteristics for cores on a CMP
    - Near Threshold Voltage (NTV)
  - Fault resilience introduces inhomogeneity in execution rates
    - error correction is not instantaneous
    - And this will get WAY worse if we move towards software-based resilience

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### Assumptions of Uniformity is Breaking

*(many new sources of heterogeneity)*

**Heterogeneous compute engines (hybrid/GPU computing)**

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### Just Speeding up Components is Design Optimization

*The really big opportunities for energy efficiency require codesign!*

**Bulk Synchronous Execution Model**

- Energy-limited design is a zero-sum-game
  - For every feature you ask for, you need to give something up
  - This is the “ground floor” for Co-Design
- Improving energy efficiency or performance of individual components doesn’t really need co-design
  - Memory is faster, then odds are that the software will run faster
  - if its better, that’s good!

### Example Near Threshold Voltage (NTV): Shekhar Borkar

*The really big opportunities for energy efficiency require codesign!*

**Bulk Synchronous Execution**

- The really \*big\* opportunities to improve energy efficiency may require a shift in how we program systems
  - This requires codesign to evaluate the hardware and new software together
  - HW/SW Interaction unknown (requires HW/SW codesign)
- If software CANNOT exploit these radical hardware concepts (such as NTV), then it would be better to not have done anything at all!

Conventional

f	f	f	f
f	f	f	f
f	f	f	f

NTV

f/2	f/4	f	f/2
f/4	f	f/2	f/4
f	f/2	f/4	f

Fig: Shekhar Borkar

### Assumptions of Uniformity is Breaking

*(many new sources of heterogeneity)*

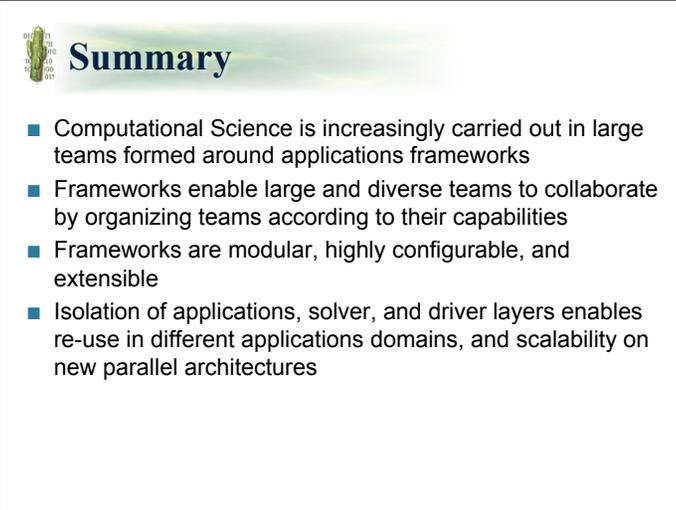
**Bulk Synchronous Execution (now)**

**Bulk Synchronous Execution (later)**

**Asynchronous Execution Model**

**In this situation, AMR might be the solution (not the problem)**





## Summary

- Computational Science is increasingly carried out in large teams formed around applications frameworks
- Frameworks enable large and diverse teams to collaborate by organizing teams according to their capabilities
- Frameworks are modular, highly configurable, and extensible
- Isolation of applications, solver, and driver layers enables re-use in different applications domains, and scalability on new parallel architectures

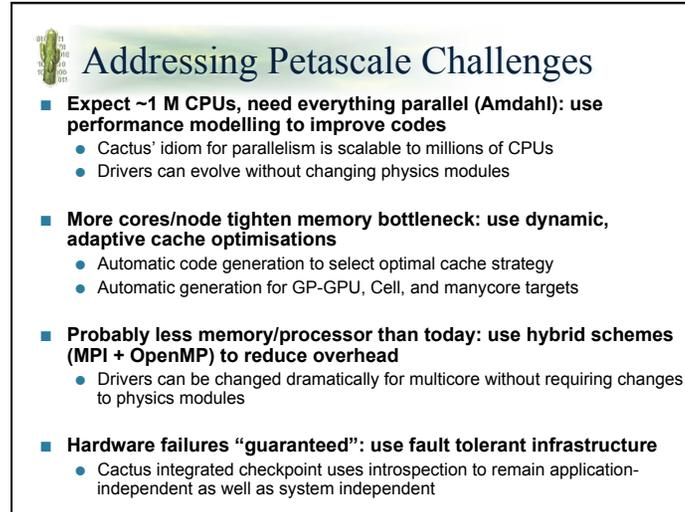


## The End




## Chapter III

### Addressing Petscale and Exascale Challenges

## Addressing Petascale Challenges

- **Expect ~1 M CPUs, need everything parallel (Amdahl): use performance modelling to improve codes**
  - Cactus' idiom for parallelism is scalable to millions of CPUs
  - Drivers can evolve without changing physics modules
- **More cores/node tighten memory bottleneck: use dynamic, adaptive cache optimisations**
  - Automatic code generation to select optimal cache strategy
  - Automatic generation for GP-GPU, Cell, and manycore targets
- **Probably less memory/processor than today: use hybrid schemes (MPI + OpenMP) to reduce overhead**
  - Drivers can be changed dramatically for multicore without requiring changes to physics modules
- **Hardware failures "guaranteed": use fault tolerant infrastructure**
  - Cactus integrated checkpoint uses introspection to remain application-independent as well as system independent

### XiRel: Improve Computational Infrastructure

- Sponsored by NSF PIF; collaboration between LSU/ PSU/RIT/AEI
- Improve mesh refinement capabilities in Cactus, based on Carpet
- Prepare numerical relativity codes for petascale architectures
- Enhance and create new physics infrastructure for numerical relativity
- Develop common data and metadata management methods, with numrel as driver application

### Cactus, Eclipse, Blue Waters (NSF Track-1 Supercomputing Project)

The diagram illustrates a workflow centered around an Eclipse IDE. Arrows indicate the flow of information:
 

- Source code** (cvs/svn, edit, compile, debug) connects to the Eclipse IDE via 'local' and 'remote' paths.
- Performance data** (gather, process, display) is generated from the Eclipse IDE.
- Simulations** (submit, monitor, steer) are managed through the Eclipse IDE.
- Online databases** (Configuration files, Performance data) are linked to the Eclipse IDE.

### Application-Level Debugging and Profiling

- Sponsored by NSF SDCI
- As framework, Cactus has complete overview over programme and execution schedule
- Need to debug simulation at level of interacting components, in production situations, at scale
- Grid function declarations have rich semantics -- use this for visual debugging
- Combine profiling information with execution schedule, place calliper points automatically

### Remote Visualization

This slide displays a collection of visualization tools used for remote visualization:
 

- OpenDX**: A 3D visualization of a simulation grid.
- LCAVision**: A visualization of a complex, multi-colored structure.
- Amira**: A 3D visualization of a biological or anatomical structure.
- Visaput**: A visualization of a 3D volume with source points.
- xgraph**: A 2D line graph showing multiple data series.
- IsoView**: A 3D visualization of a pink, irregularly shaped object.
- gnuplot**: A 3D surface plot showing a landscape-like structure.

 The URL [www.cactuscode.org/VizTools](http://www.cactuscode.org/VizTools) is provided at the bottom.

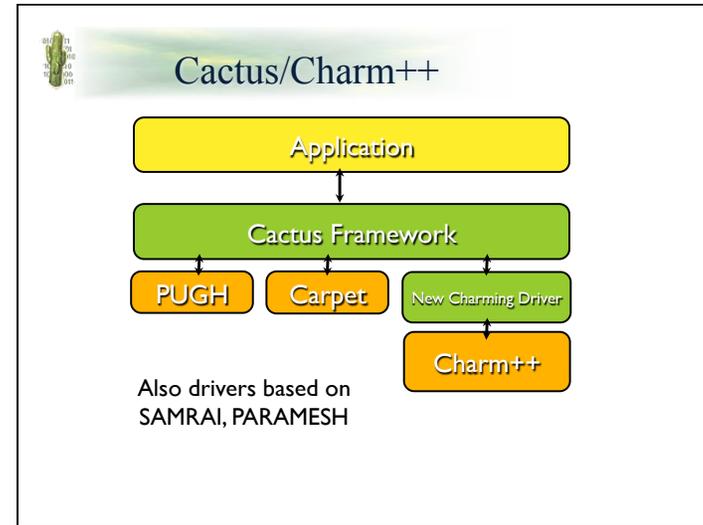
### Task Farm/Remote Viz/Steer Capabilities

Big BH Sim (LBL, NCSA, PSC, ...)

Visapult BWC

Baltimore

Current TFM Status in portal...



### Summary of Cactus Capabilities

- Variety of science domains (highly configurable)
- Multi-Physics (modular)
- Petascale (tractable programming model for massive concurrency, performance, debugging, reliability)
- Combining HPC (batch systems) and interactivity (GUI), where possible
- Framework -- for any content

## Chapter IV

# Extra Material

## Framework Components

- **Flesh: *The glue that ties everything together (C&C language)***
  - Supports composition of modules into applications (targets non-CS-experts)
  - Invokes modules in correct order (baseline scheduling)
  - Implements code build system (get rid of makefiles)
  - Implements parameter file parsing
  - Generates bindings for any language (Fortran, C, C++, Java)
- **Driver: *Implements idiom for parallelism***
  - Implements "dwarf-specific" composite datatypes
  - Handles data allocation and placement (domain decomposition)
  - Implements communication pattern for "idiom for parallelism"
  - Implements thread-creation and scheduling for parallelism
- **Solver/Module: *A component implementing algorithm or other composable function***
  - Can be written in any language (flesh handles bindings automatically)
  - Implementation of parallelism externalized, so developer writes nominally serial code with correct idiom. Parallelism handled by the "driver".
  - Thorns implementing same functionality derived from same 'abstract class' of functionality such as "elliptic solver" (can have many implementations of elliptic solve. Select at compile time and/or at runtime)

## More Information

- **The Science of Numerical Relativity**
  - <http://jean-luc.aei.mpg.de>
  - <http://dsc.discovery.com/schedule/episode.jsp?episode=23428000>
  - <http://www.appleswithapples.org/>
- **Cactus Community Code**
  - <http://www.cct.lsu.edu>
  - <http://www.cactuscode.org/>
  - <http://www.carpetcode.org/>
- **Grid Computing with Cactus**
  - <http://www.astrogrid.org/>
- **Benchmarking Cactus on the Leading HPC Systems**
  - <http://crd.lbl.gov/~oliker>
  - <http://www.nersc.gov/projects/SDSA/reports>



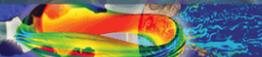
Lawrence Berkeley National Laboratory / National Energy Research Supercomputing Center

### Examples: Chombo AMR



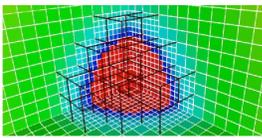
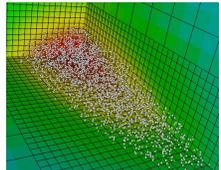
CRD

high performance computing  
research department

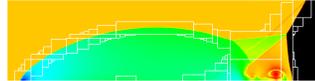
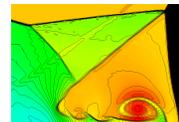


## Block-Structured Local Refinement

- Refined regions are organized into rectangular patches.

- Refinement in time as well as in space for time-dependent problems.
- Local refinement can be applied to any structured-grid data, such as bin-sorted particles.

### Cartesian Grid Representation of Irregular Boundaries

Based on nodal-point representation (Shortley and Weller, 1938) or finite-volume representation (Noh, 1964).

$$\nabla \cdot \vec{F} \approx \frac{1}{\kappa h^d} \int \nabla \cdot \vec{F} dx = \frac{1}{\kappa h} \sum \alpha_s \vec{F}_s \cdot \vec{n}_s + \alpha_B \vec{F} \cdot \vec{n}_B \equiv D \cdot \vec{F}$$

Advantages:

- Grid generation is easy.
- Good discretization technology (e.g. finite differences on rectangular grids, geometric multigrid)
- Straightforward coupling to AMR (in fact, AMR is essential).

### Efficient Embedded Boundary Multigrid Solvers

- In the EB case, the matrices are not symmetric, but they are sufficiently close to M-matrices for multigrid to work (nontrivial to arrange this in 3D).
- A key step in multigrid algorithms is *coarsening*. In the non-EB case, computing the relationship between the locations of the coarse and fine data involves simple integer arithmetic. In the EB case, both the data access and the averaging operations are more complicated.
- It is essential that coarsening a geometry preserves the *topology* of the finer EB representation.

### A Software Framework for Structured-Grid Applications

The empirical nature of multiphysics code development places a premium on the availability of a diverse and agile software toolset that enables experimentation. We accomplish this with a software architecture made up of reusable tested components organized into layers.

- **Layer 1:** Data and operations on unions of rectangles - set calculus, rectangular array library (with interface to Fortran), Data on unions of rectangles, with SPMD parallelism implemented by distributing boxes to processors. Load balancing tools (e.g., SFC).
- **Layer 2:** Tools for managing interactions between different levels of refinement in an AMR calculation - interpolation, averaging operators, coarse-fine boundary conditions.
- **Layer 3:** Solver libraries - multigrid solvers on unions of rectangles, AMR hierarchies; hyperbolic solvers; AMR time stepping.
- **Layer 4:** Complete parallel applications.
- **Utility Layer:** Support, interoperability libraries - API for HDF5 I/O, AMR data alias.

### Mechanisms for Reuse

- **Algorithmic reuse.** Identify mathematical components that cut across applications. Easy example: solvers. Less easy example: Layer 2.
- **Reuse by templating data holders.** Easy example: rectangular array library - array values are the template type. Less easy example: data on unions of rectangles - "rectangular array" is a template type.

- **Reuse by inheritance.** Control structures (Iterative solvers, Berger-Oliger timestepping) are independent of the data, operations on that data. Use inheritance to isolate the control structure from the details of what is being controlled (interface classes).

### Examples of Layer 1 Classes (BoxTools)

- IntVect**  $i \in \mathbb{Z}^d$ . Can translate  $i_1, i_2$ , coarsen  $i/s$ , refine  $i \cdot s$ .
- Box**  $B \in \mathbb{Z}^d$  is a rectangle:  $B = [i_{low}, i_{high}]$ .  $B$  can be translated, coarsened, refined. Supports different centerings (node-centered vs. cell-centered) in each coordinate direction.
- IntVectSet**  $I \in \mathbb{Z}^d$  is an arbitrary subset of  $\mathbb{Z}^d$ .  $I$  can be shifted, coarsened, refined. One can take unions and intersections, with other **IntVectSets** and with **Boxes**, and iterate over an **IntVectSet**.
- FArrayBox**  $A(\text{Box } B, \text{int } n\text{Comps})$ : multidimensional arrays of doubles or floats constructed with  $B$  specifying the range of indices in space,  $n\text{Comp}$  the number of components. `Real* FArrayBox::dataPtr` returns the pointer to the contiguous block of data that can be passed to Fortran.

### Layer 1 Reuse: Distributed Data on Unions of Rectangles

Provides a general mechanism for distributing data defined on unions of rectangles onto processors, and communication between processors.

- Metadata of which all processors have a copy: **BoxLayout** is a collection of **Boxes** and processor assignments:  $\{B_k, p_k\}_{k=1}^{n\text{Grids}}$ . **DisjointBoxLayout**: public **BoxLayout** is a **BoxLayout** for which the **Boxes** must be disjoint.
- template `<class T> LevelData<T>` and other container classes hold data distributed over multiple processors. For each  $k=1 \dots n\text{Grids}$ , an "array" of type  $T$  corresponding to the box  $B_k$  is located on processor  $p_k$ . Straightforward API's for copying, exchanging ghost cell data, iterating over the arrays on your processor in a SPMD manner.

### Example: explicit heat equation solver, parallel case

- `LevelData<T>::exchange()`: obtains ghost cell data from valid regions on other patches
- `DataIterator`: iterates over only the patches that are owned on the current processor.

### First Light on LMC (AMR) Code Control Dependencies

12  
8



### AMR Utility Layer

- API for HDF5 I/O.
- Interoperability tools. We have developed a framework-neutral representation for pointers to AMR data, using opaque handles. This will allow us to wrap Chombo classes with a C interface and call them from other AMR applications.
- Chombo Fortran - a macro package for writing dimension-independent Fortran and managing the Fortran / C interface.
- Parmparse class from BoxLib for handling input files.
- Visualization and analysis tools (Vistl).



### Spiral Design Approach to Software Development

Scientific software development is inherently high-risk: multiple experimental platforms, algorithmic uncertainties, performance requirements at the highest level. The Spiral Design approach allows one to manage that risk, by allowing multiple passes at the software and providing a high degree of schedule visibility.

Software components are developed in phases.

- Design and implement a basic framework for a given algorithm domain (EB, particles, etc.), implementing the tools required to develop a given class of applications.
- Implement one or more prototype applications as benchmarks.
- Use the benchmark codes as a basis for measuring performance and evaluating design space flexibility and robustness. Modify the framework as appropriate.
- The framework and applications are released, with user documentation, regression testing, and configuration for multiple platforms.



### Software Engineering Plan

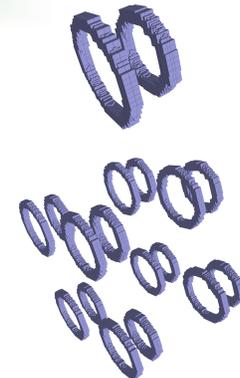
- All software is open source: <http://seesar.lbl.gov/anag/software.html>.
- Documentation: algorithm, software design documents; *Doxygen* manual generation; users' guides.
- Implementation discipline: CVS source code control, coding standards.
- Portability and robustness: flexible make-based system, regression testing.
- Interoperability: C interfaces, opaque handles, permit interoperability across a variety of languages (C++, Fortran 77, Python, Fortran 90). Adaptors for large data items a serious issue, must be custom-designed for each application.



### Replication Scaling Benchmarks

- Take a single grid hierarchy, and scale up the problem by making identical copies. Full AMR code (processor assignment, remaining problem setup) is done without knowledge of replication.

- Good proxy for some kinds of applications scaleup.
- Tests algorithmic weak scalability and overall performance.
- Avoids problems with interpreting scalability of more conventional mesh refinement studies with AMR.



### Replication Scaling of AMR: Cray XT4 Results

**PPM gas dynamics solver:**

- 97% efficient scaled speedup over range of 128-8192 processors (176-181 seconds).
- Fraction of operator peak: 90% (480 Mflops / processor).
- Adaptivity Factor: 16.

**AMR-multigrid Poisson solver:**

- 87% efficient scaled speedup over range of 256-8192 processors (8.4-9.5 seconds).
- Fraction of operator peak: 45% (375 Mflops / processor).
- Adaptivity factor: 48.

### Embedded Boundary Performance Optimization and Scaling

- Aggregate stencil operations, which use pointers to data in memory and integer offsets, improve serial performance by a factor of 100.
- Template design
  - Implement AMRMultigrid once and re-use across multiple operators
- Operator-dependent load balancing
- space-filling curve algorithm to order boxes (Morton)
  - Minimization of communication
- Relaxing about relaxation
  - gsrb vs. multi-color.
  - edge and corner trimming of boxes
- And many many more

### Communication Avoiding Optimizations

- Distributing patches to processors to maximize locality. Sort the patches by Morton ordering, and divide into equal-sized intervals.
- Overlapping local copying and MPI communications in exchanging ghost-cell data (only has an impact at 4096, 8192).
- Exchanging ghost-cell data less frequently in point relaxation.

### Chombo AMR Capabilities

- Single-level, multilevel solvers for cell-centered and node-centered discretizations of elliptic / parabolic systems.
- Explicit methods for hyperbolic conservation laws, with well-defined interface to physics-dependent components.
- Embedded boundary versions of these solvers.
- Extensions to high-order accuracy, mapped grids (under development).
- AMR-PIC for Vlasov-Poisson.
- Applications:
  - Gas dynamics with self gravity. Coupling to AMR-PIC.
  - Incompressible Navier-Stokes Equations.
  - Resistive magnetohydrodynamics.
- Interfaces to HDF5 I/O, hypre, VisIt.
- Extensive suite of documentation. Code and documentation released in public domain. New release of Chombo in Spring 2009 will include embedded boundary capabilities (google "Chombo").