Programming with Parallel Objects

Session 1: Fundamentals of Parallel Objects Programming

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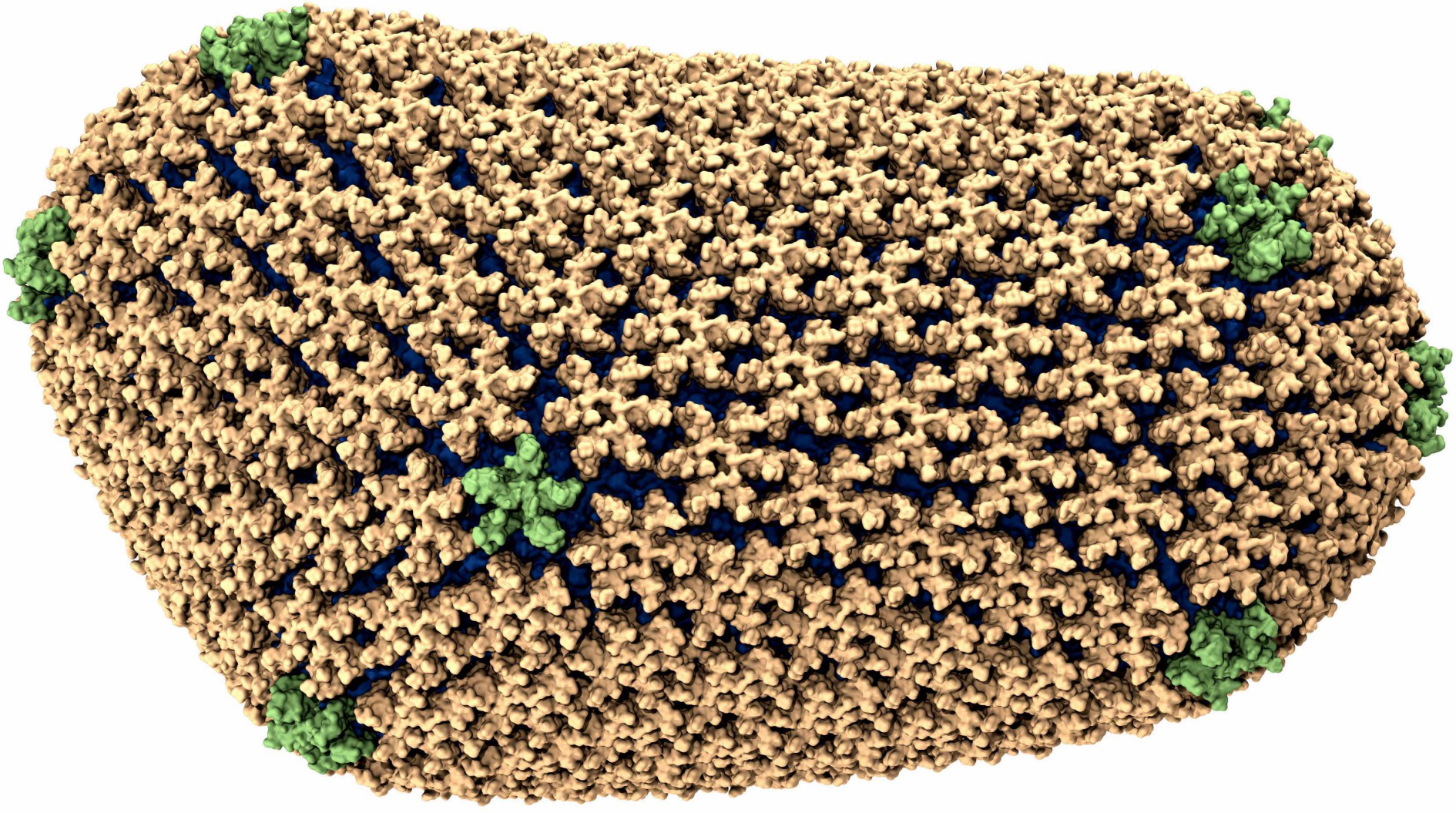
ACKNOWLEDGEMENTS

Most of the content of this tutorial was provided courtesy of Prof. Laxmikant V. Kalé from the Parallel Programming Laboratory (PPL) of the University of Illinois at Urbana-Champaign. The PPL originally developed the ideas behind parallel object programming and has maintained the Charm++ code base for more than 20 years.

ADMINISTRATIVIA

- Official Charm++ website:
  http://www.charmplusplus.org/
- Slides and code for this tutorial:
  https://github.com/emenesesrojas/parallel_objects.git
- Questions on parallel objects programming:
  https://ecar2017.slack.com
- Advanced questions on Charm++:
  ppl@cs.illinois.edu
- Official instructor's email address:
  emeneses@cenat.ac.cr



Structure of HIV capsid

Theoretical and Computational Biophysics Group
University of Illinois at Urbana-Champaign

Outline

Challenges in High Performance Computing

Introduction
- Object Design
- Execution Model

Hello World

Benefits of Charm++

Charm++ Programming Language
- Charm++ Basics
- Object Collections

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Harnessing Parallelism

Trends in system architecture

- Frequencies have stopped increasing
- Memory costs are high
  - Relatively low per core memory
- Increasing heterogeneity
  - Accelerators, simultaneous multithreading (SMT)
- Energy, power, and thermal considerations
- Frequent component failures

Harnessing Parallelism

High concurrency

- Compute resources are not faster cores, but **more cores**
- Unprecedented levels of available concurrency:

Rank*	Machine	Cores
1	NRCPC Sunway TaihuLight	10,649,600
2	NUDT Tianhe-2	3,120,000
5	IBM BG/Q Sequoia	1,572,864
8	Fujitsu K computer	705,024
6	Cray XC40 Cori	622,336

* Top 500 list, June 2017

- Mid-size clusters will be ubiquitous
- Each thread of execution has to:
  - operate on lesser data
  - wait relatively longer for remote data
- Have to operate in **strong scaling** regime

Harnessing Parallelism

Next-generation applications

- Need for strong scaling
  - faster solutions (not just larger problems)
- Application characteristics
  - Multi-resolution
    - Adaptive, spatial and temporal resolutions
    - Dynamic/adaptive refinements: to handle application variation
  - Multi-module (multi-physics)
    - Complex physics in multiple, interacting modules
  - Adapt to a volatile computational environment
  - Exploit heterogeneous architecture
  - Deal with thermal and energy considerations
- Consequences:
  - Must support automated resource management
  - Must support interoperability and parallel composition

Harnessing Parallelism

MPI programming model

- Highly successful
- Universally used
- Has supported application evolution from gigascale to petascale

- Library
- Communication primitives

- MPI does not directly support automated resource management (e.g. load balancing, fault tolerance, etc.)

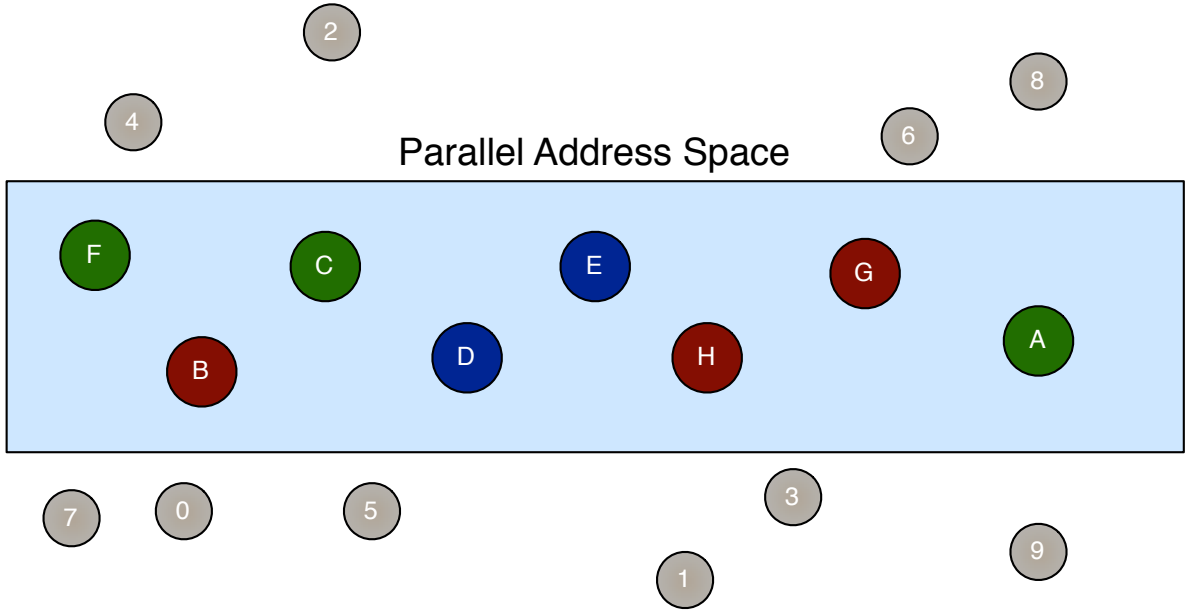
Stuff you Already Know

Benefits of object-based code

- Objects encapsulate data
- Methods represent functionality relevant to that data
- Method invocations can modify/update state of the object/data
- Computation can be expressed in terms of objects interacting via method invocations
- Methods are natural units of sequential computation on object data
- Thoughtful design yields focused methods with single purpose
- Naturally expresses an object's response to inputs (signals/data)
- Nothing new
- Still quite uncommon in HPC code
- It's not about language syntax, it's about program structure

Globally-visible Objects

Called chares (from "chores")



- Certain "special" object *instances* are:
  - first-class citizens in the parallel address space
  - with unique location-independent names
- Under the hood, the runtime handles locality and provides the mechanisms to promote objects to the parallel space

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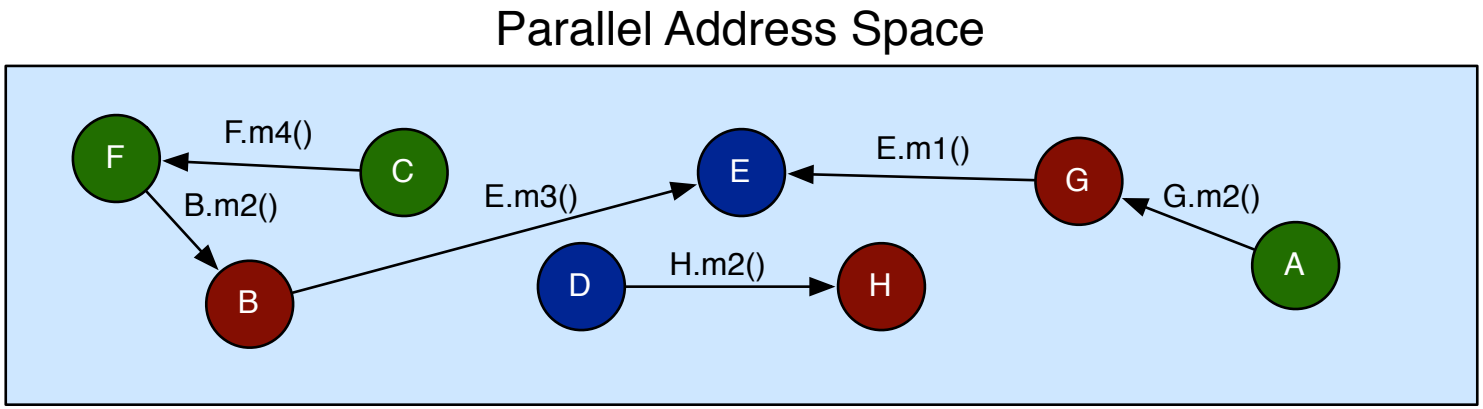
Globally-visible Methods

Entry methods



- How can objects communicate across address spaces?
  - Just like a sequential object-oriented language, an object's reference is used to invoke a method
  - In the parallel space, this is a handle that is location transparent
  - A method invocation becomes an act of communication

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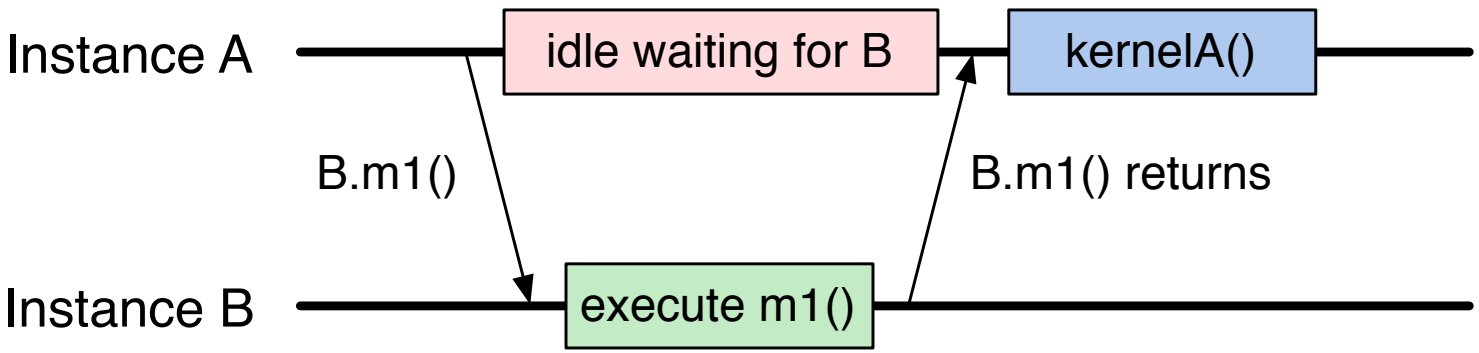
Method-driven Asynchronous Communication

Message-driven execution



- What happens if an object waits for a return value from a method invocation?
  - Performance
  - Latency
  - Reasoning about correctness

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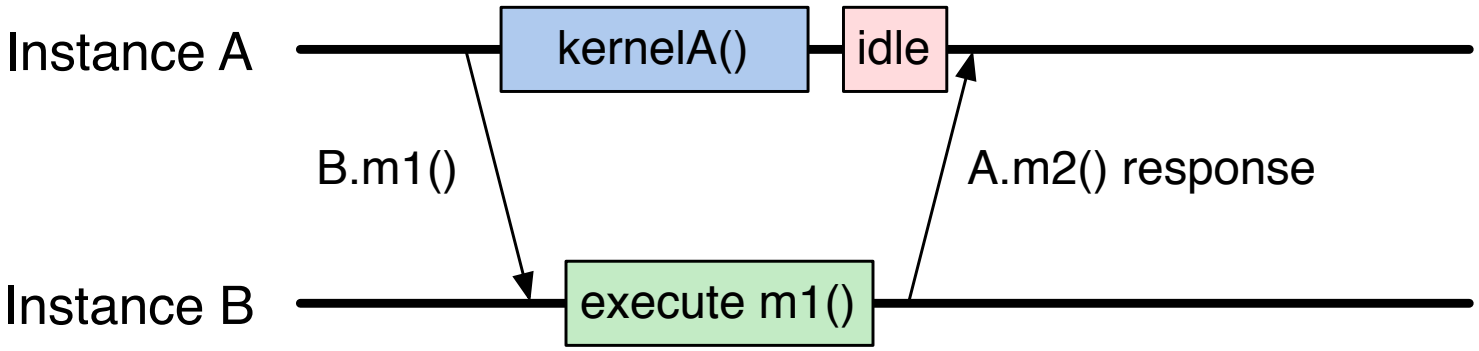
Design Principle

Do not wait for remote completion



- Hence, method invocations should be asynchronous
  - No return values
- Computations are driven by the incoming data
  - Initiated by the sender or method caller

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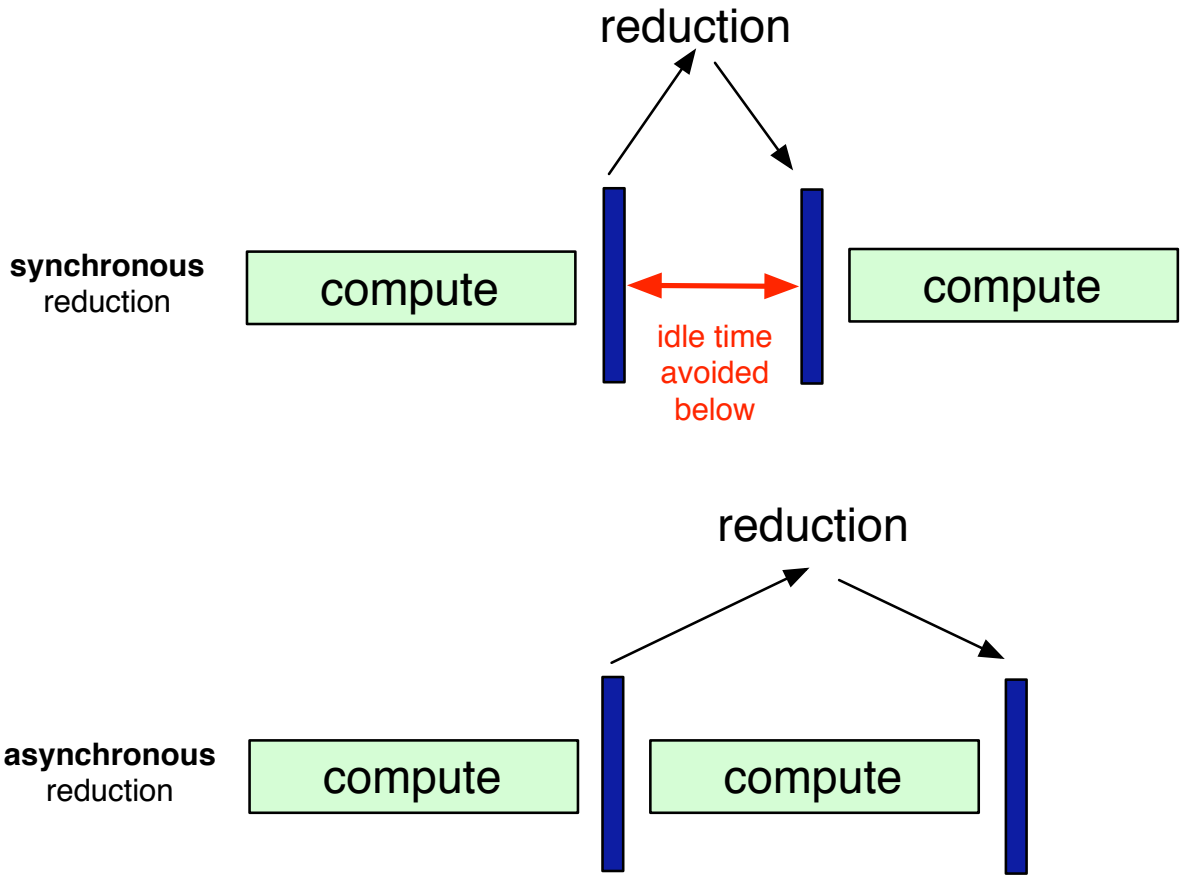
Example

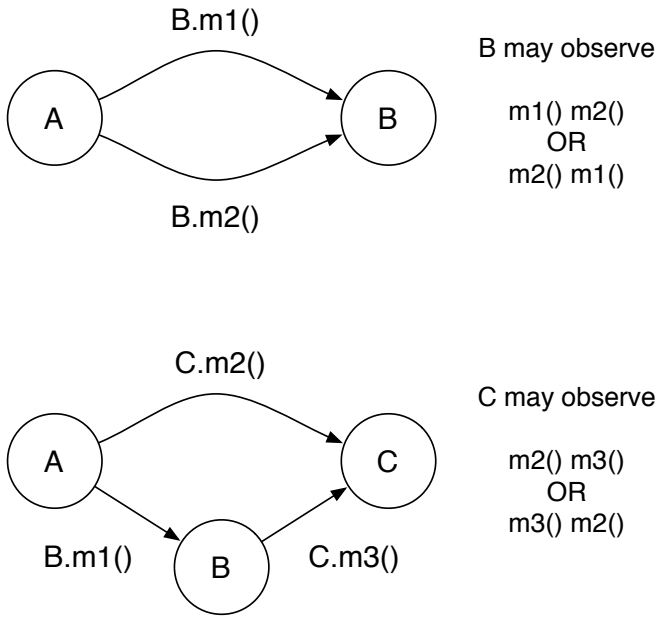
Jacobi reduction



Methods

Natural units of sequential computation

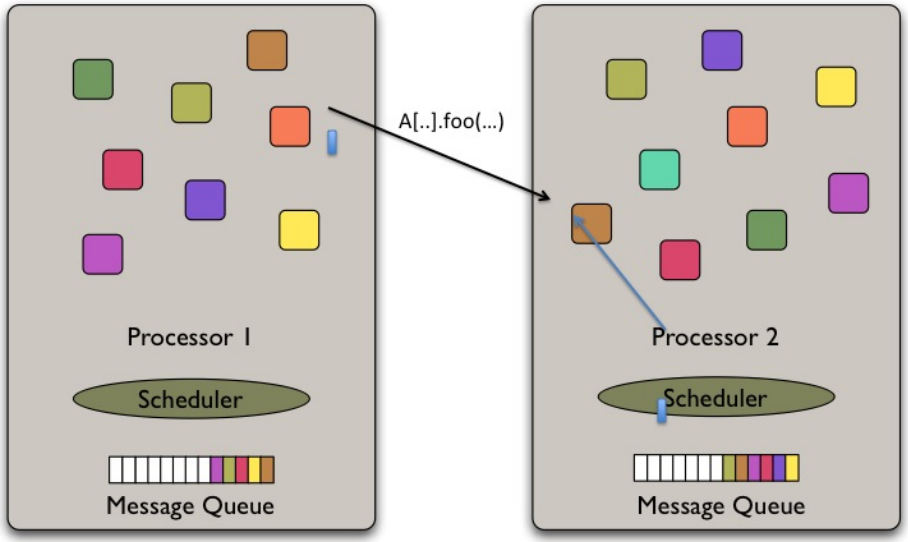
- Methods still have the same sequential semantics
  - Atomicity: methods do not execute in parallel
- Methods cannot be interrupted or preempted
- Methods interact and update state of an object in the same way
- Method sequencing is what changes from sequential computation



The Execution Model

Messages and schedulers

- Several objects live on a single *processing entity (PE)*
  - For now, think of it as a core (or just "processor")
- As a result,
  - Method invocations directed at objects on that processor will have to be stored in a pool
  - A user-level scheduler will select one invocation from the queue and runs it to completion
  - A PE is the entity that has one scheduler instance associated with it



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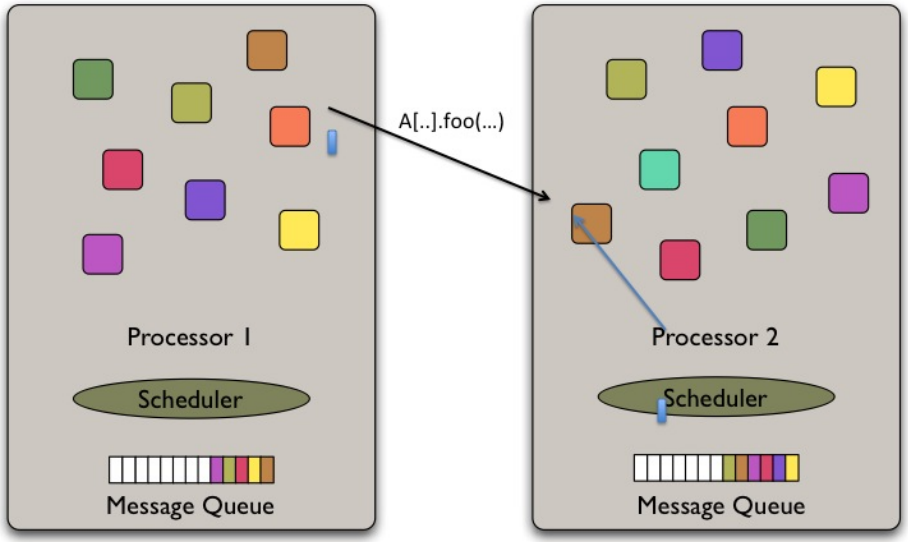
Message-driven Execution

Objects are reactive entities

- Execution is triggered by availability of a "message" (a method invocation)
- When an entry method executes:
  - it may generate messages for other objects
  - the *runtime system* (RTS) deposits them in the message Q on the target processor



Example

Hello World

- `hello.ci` file

```
mainmodule hello {
  mainchare Main {
    entry Main(CkArgMsg *m);
  };
};
```

- `hello.cpp` file

```
#include <stdio.h>
#include "hello.decl.h"

class Main : public CBase_Main {
  public: Main(CkArgMsg* m) {
    ckout << "Hello World!" << endl;
    CkExit();
  };
};

#include "hello.def.h"
```

Example

Hello World with chares

`hello.ci` file

```
mainmodule hello {
  mainchare Main {
   entry Main(CkArgMsg *m
         );
  };
  chare Singleton {
   entry Singleton();
  };
};
```

`hello.cpp` file

```
#include <stdio.h>
#include "hello.decl.h"

class Main : public CBase_Main {
  public: Main(CkArgMsg* m) {
    CProxy_Singleton::ckNew();
  };
};

class Singleton : public
      CBase_Singleton {
  public: Singleton() {
    ckout << "Hello World!" <<
          endl;
    CkExit();
  };
};
#include "hello.def.h"
```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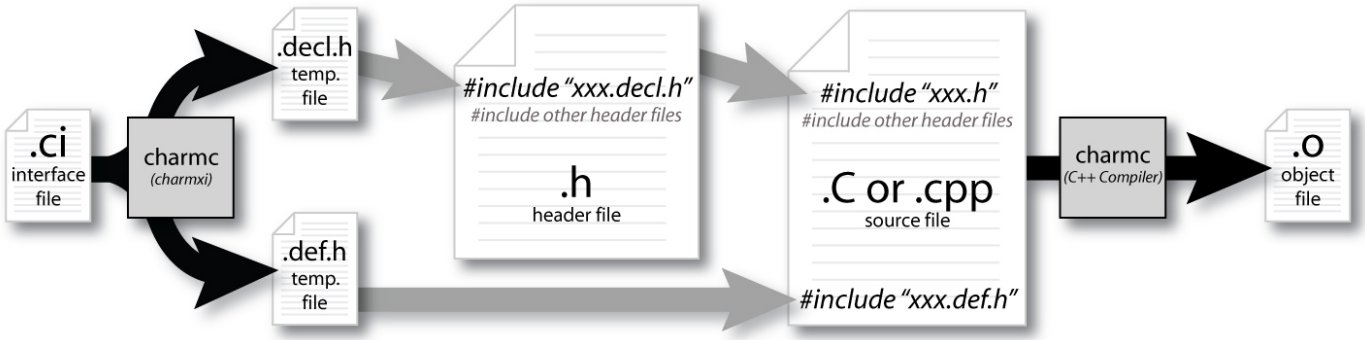
Compiling a Charm++ Program

Charm++ and C++ compilers



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Compilation Example

Hello World

- Compiling
  - `charmc hello.ci`
  - `charmc -c hello.C`
  - `charmc -o hello hello.o`
- Running
  - `./charmrun +p7 ./hello`
  - The +p7 tells the system to use seven cores

Building Charm++

1. Download the latest stable version of the code:

   `http://charmplusplus.org/download/`

2. If you are feeling adventurous, get the latest version:

   `git clone http://charm.cs.uiuc.edu/gerrit/charm`

3. Build an appropriate version of the code for you architecture:

   `./build <TARGET> <ARCH> <OPTS>`

   - `TARGET = charm++, AMPI, bgampi, LIBS, etc.`
   - `ARCH = net-linux-x86_64, multicore-darwin-x86_64, pamilrts-bluegeneq, etc.`
   - `OPTS = --with-production, --enable-tracing, xlc, smp, -j8, etc.`

4. Get familiar with Charm++:

   `http://charmplusplus.org/tutorial/`

5. Ask questions:

   `http://charm.cs.illinois.edu/manuals/html/charm++/A.html`

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Exercise 1.1

Building Charm++

Download Charm++ code base and build it for your target machine (laptop, desktop, server, supercomputer)

Examples:

- Linux cluster:

```
./build charm++ netlrts-linux-x86_64 gcc -j8 --with-production
```

- Linux cluster on MPI:

```
./build charm++ mpi-linux-x86_64 -j8 --with-production
```

- Linux laptop:

```
./build charm++ multicore-linux-x86_64 -j8 --with-production
```

- Mac laptop:

```
./build charm++ multicore-darwin-x86_64 -j8 --with-production
```

- Windows laptop with VC++:

```
./build charm++ multicore-win-x86_64 --with-production
```

Exercise 1.2

Running Charm++ Hello World

Get into Charm++'s source code and look for the Hello World example:

`charm-6.8.0/examples/charm++/hello`

Run the example

Impact on Communication

Alleviating one performance bottleneck

- Current use of communication network:
  - Compute-communicate cycles in typical MPI apps
  - Network is used for a fraction of time
  - On the critical path
- Hence, current communication networks are over-engineered by necessity
- With overdecomposition:
  - Communication is spread over an iteration
  - Adaptive overlap of communication and computation

Example

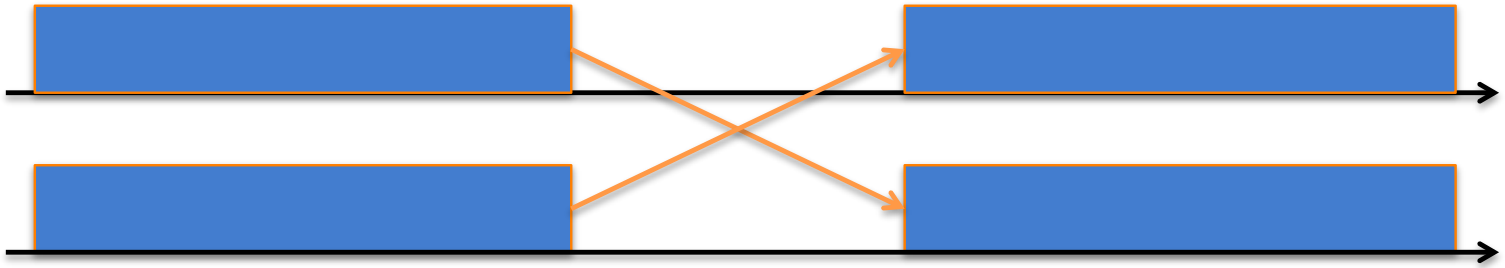
Stencil computation

- Consider a simple stencil computation
  - With traditional design based on traditional methods (e.g. MPI-based)
    - Each processor has a chunk, which alternates between computing and communicating
  - With Charm++
    - Multiple chunks on each processor
    - Wait time for each chunk overlapped with useful computation for others
    - Communication spread over time

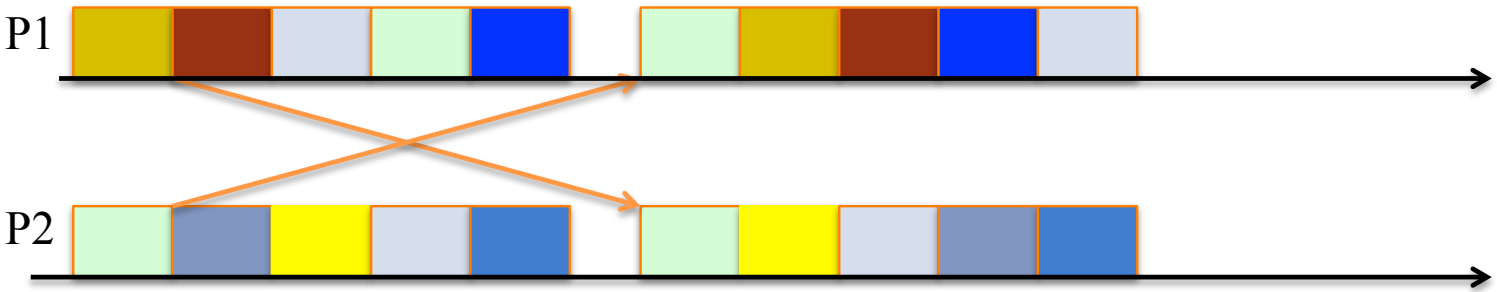
Example

Stencil computation

Stencil in MPI: No overlap among computation and communication

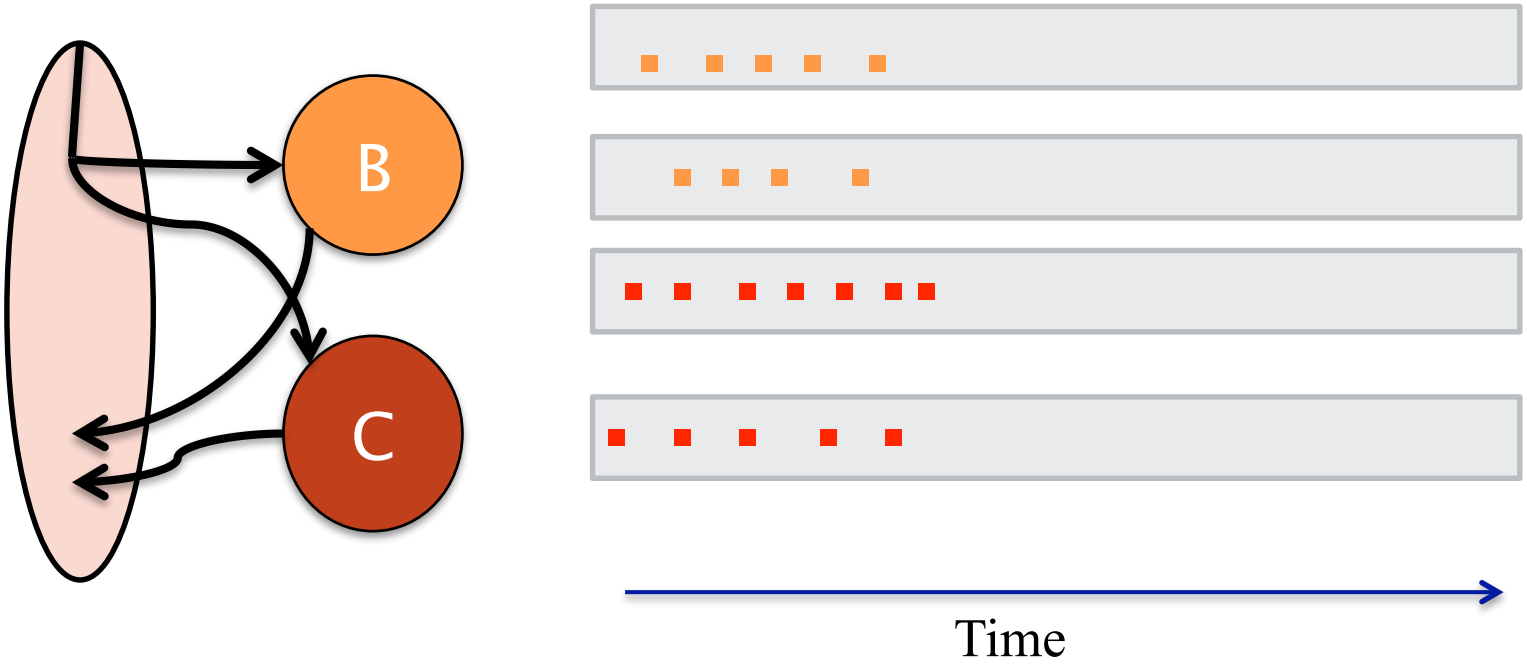


Stencil in Charm: Communication of a chare overlaps with computation of others



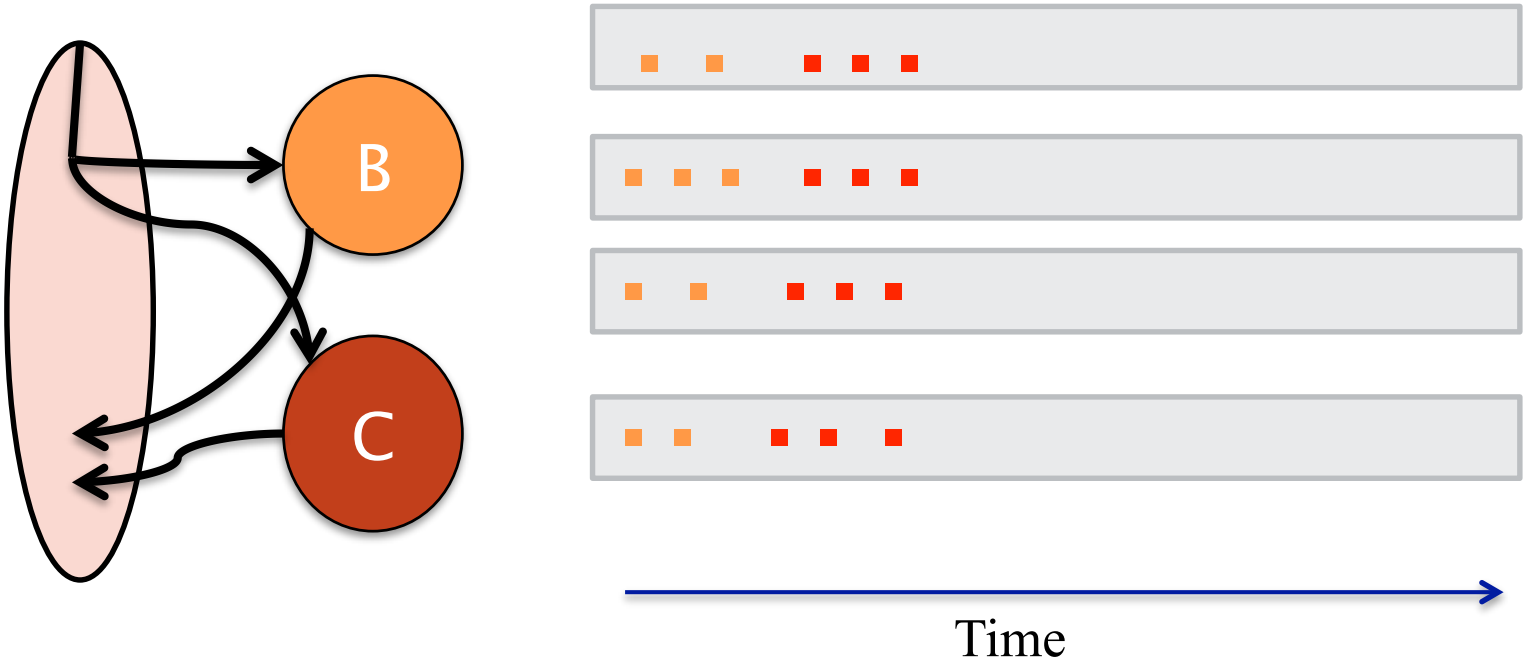
Space Division

An effect of lacking message-driven execution (and virtualization)



Sequentialization

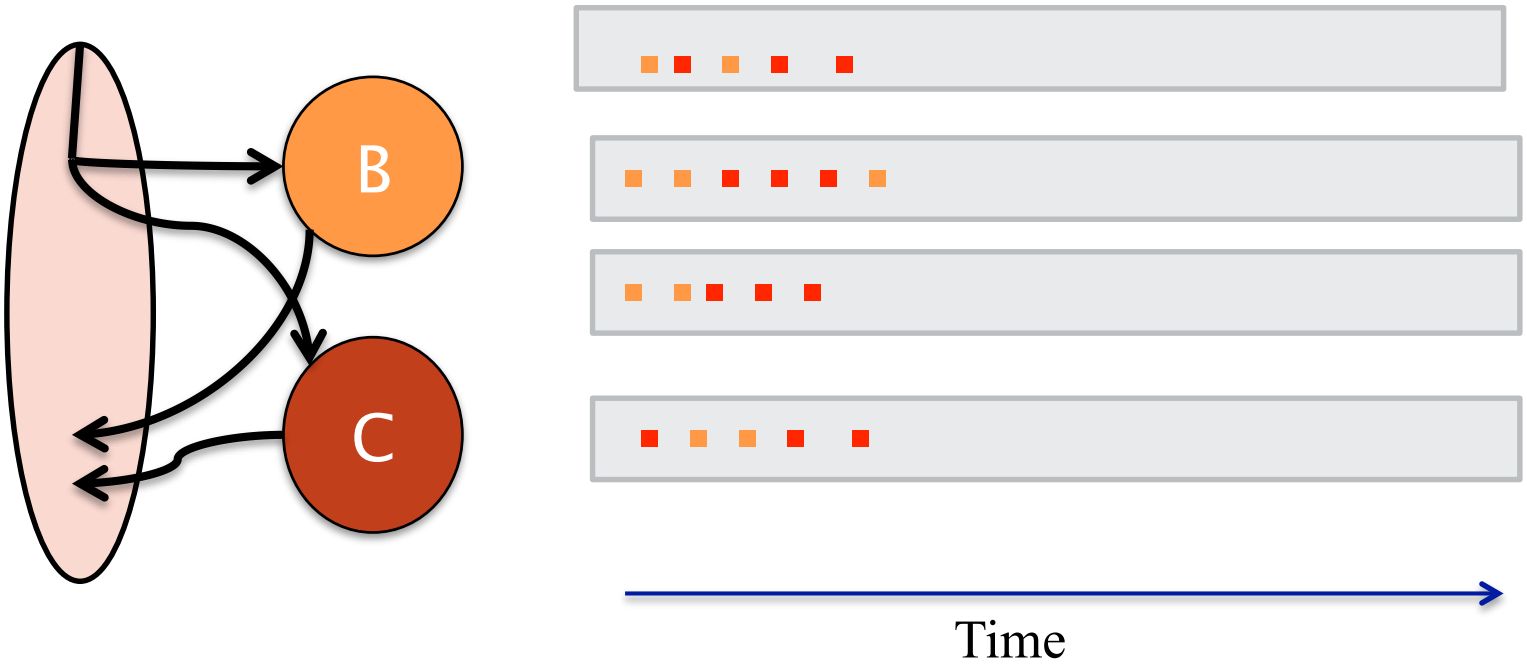
An effect of lacking message-driven execution (and virtualization)



Modularity and Compositionality

Separation of concerns

Parallel Composition: A1; (B || C); A2



Different modules, written in different languages/paradigms, can overlap in time and on processors, without programmer having to worry about this explicitly

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Migratability

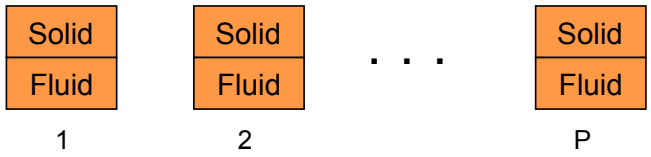
Location independence

- Once the programmer has written the code without reference to processors, all of the communication is expressed among objects
- The system is free to migrate the objects across processors as and when it pleases
  - It must ensure it can deliver method invocations to the objects, wherever they go
  - This migratability turns out to be a key attribute for empowering an adaptive runtime system

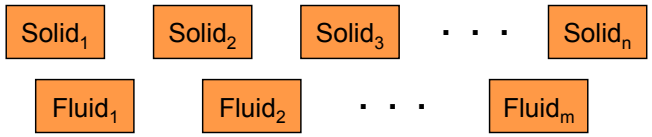
Example

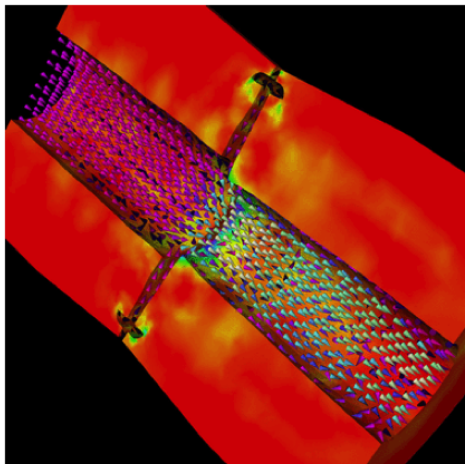
Decomposition independent of number of cores

- Rocket simulation under traditional MPI



- Rocket simulation with migratable objects





- Benefits: load balance, communication optimizations, modularity

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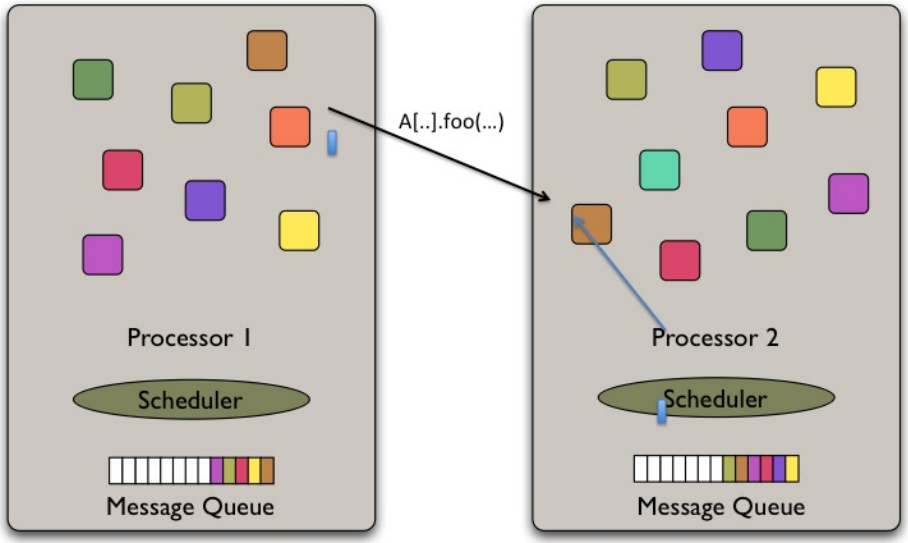
Architectures

Utility for multi-cores, many-cores, accelerators

- Objects connote and promote locality
- Message-driven execution is:
  - A strong principle of prediction for data and code use
  - Much stronger than principle of locality
    - Can be used to scale memory wall
    - Prefetching of needed data, e.g, into scratchpad memories



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Load Balancing

A major benefit of migratability

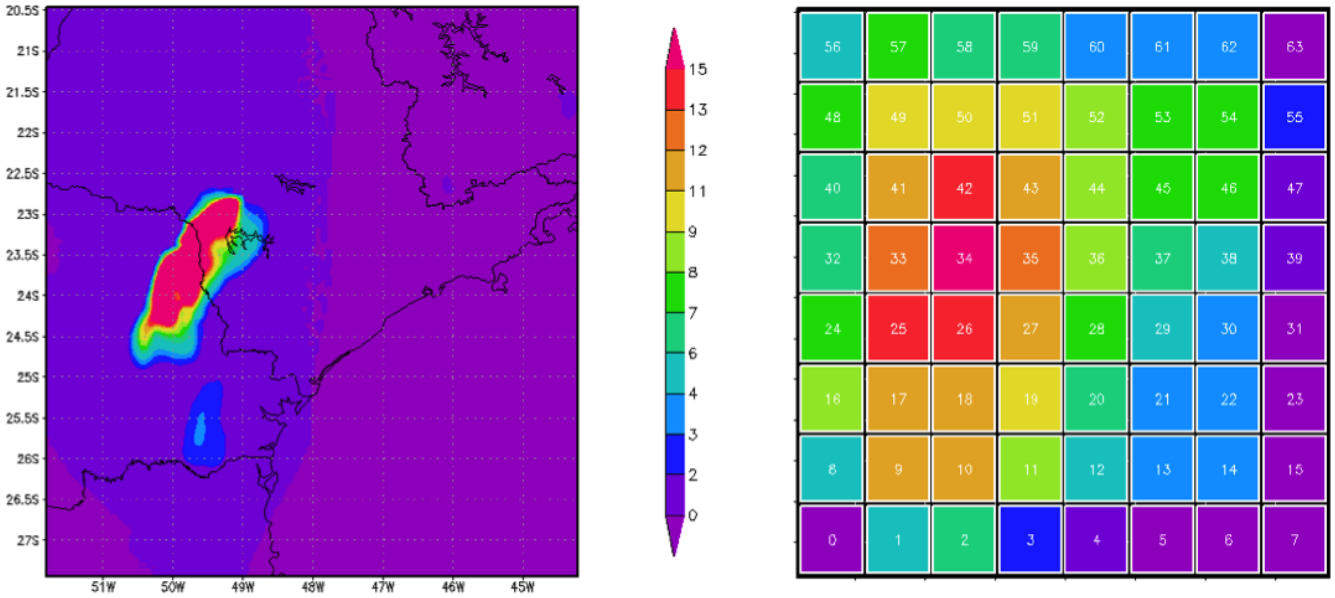
- Static
  - Irregular applications
  - Programmer shouldn't have to figure out ideal mapping
- Dynamic
  - Applications are increasingly using adaptive strategies
  - Abrupt refinements
  - Continuous migration of work (e.g. particles in MD)
- Challenges
  - Performance limited by most overloaded processor
  - The chance that one processor is severely overloaded gets higher as processor count increases

Migratable objects empower automated load balancing!

Example

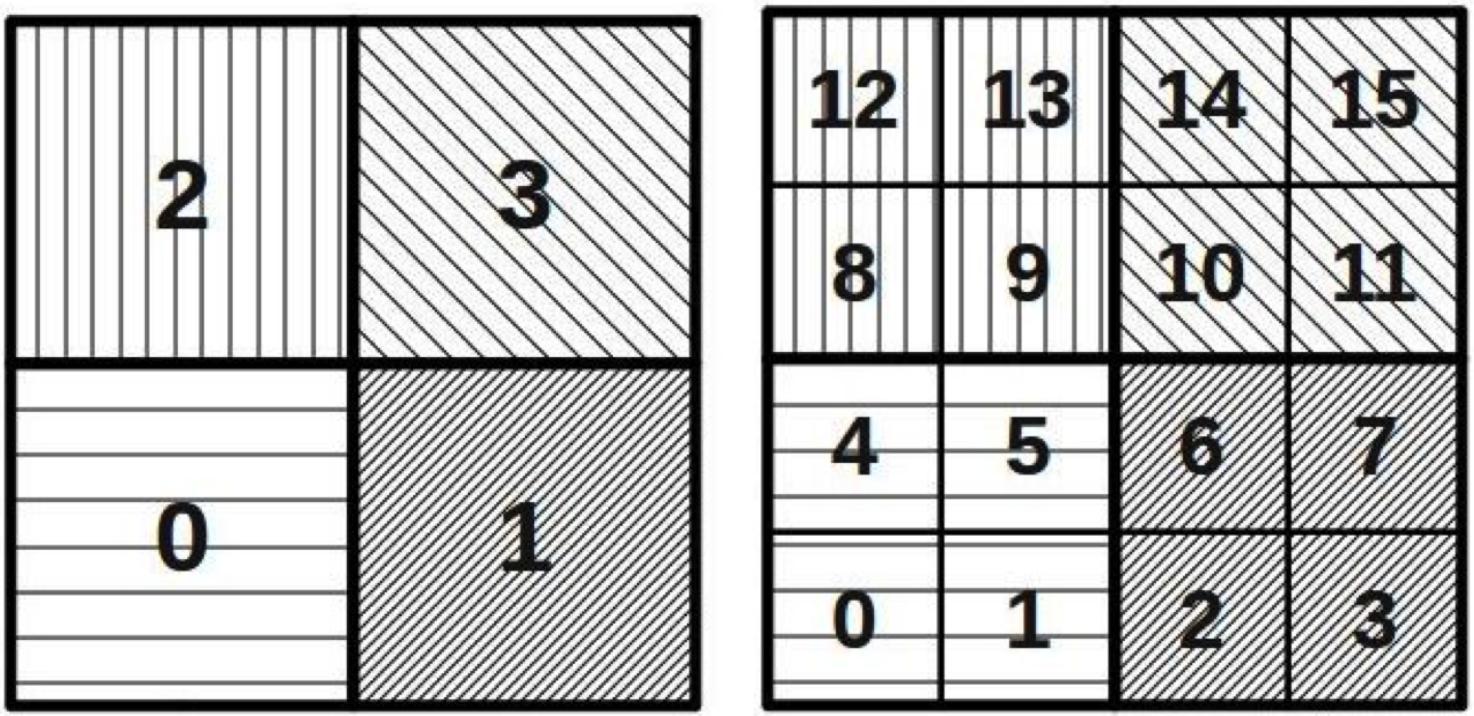
Weather forecasting in BRAMS

- BRAMS: Brazillian weather code (based on RAMS)
- AMPI version (Eduardo Rodrigues, with Dr. Celso Mendes and Prof. Jairo Panetta)



Basic Virtualization of BRAMS

Data partition



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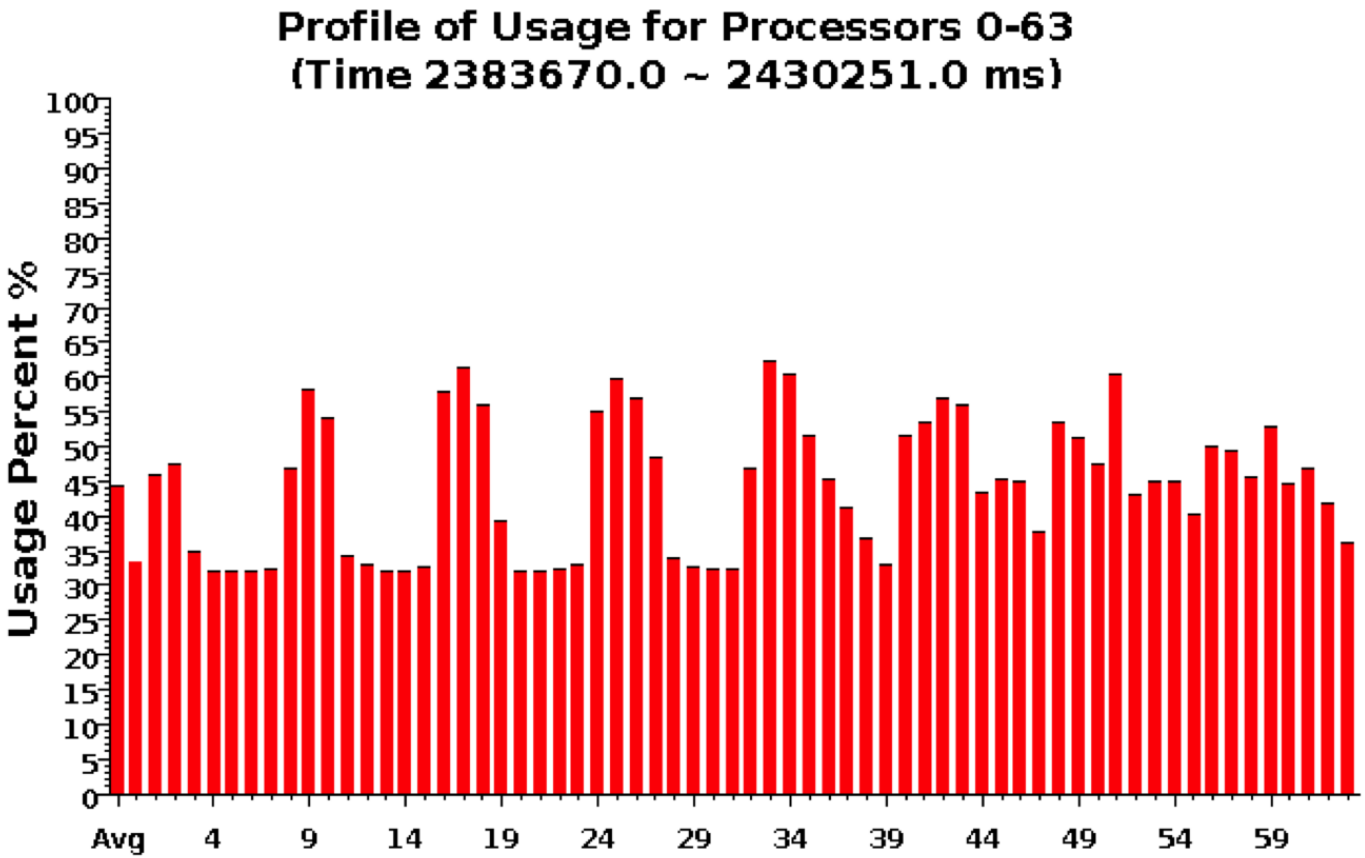
Baseline

64 objects on 64 processors



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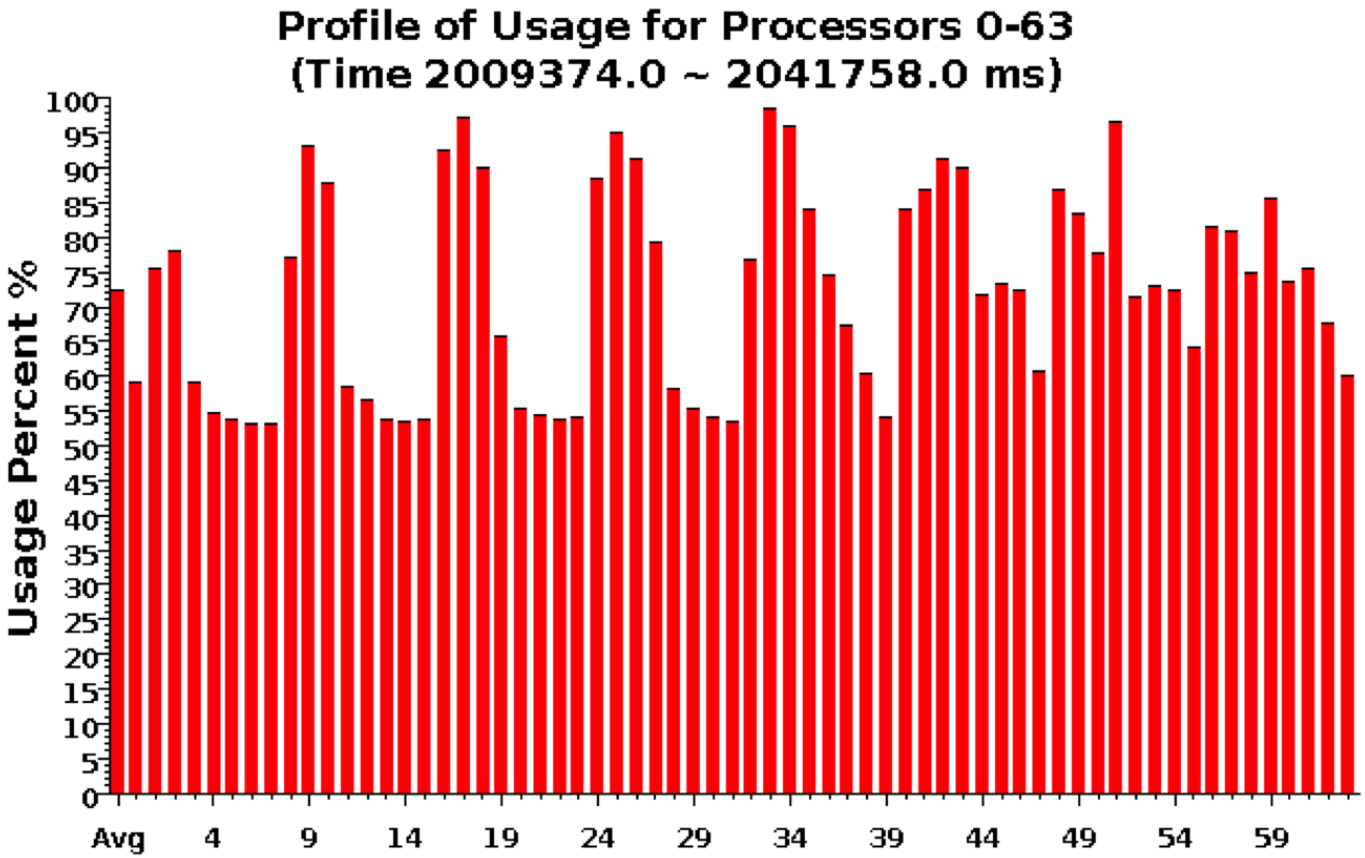
Over-decomposition

1024 objects on 64 processors



Benefits from communication/computation overlap

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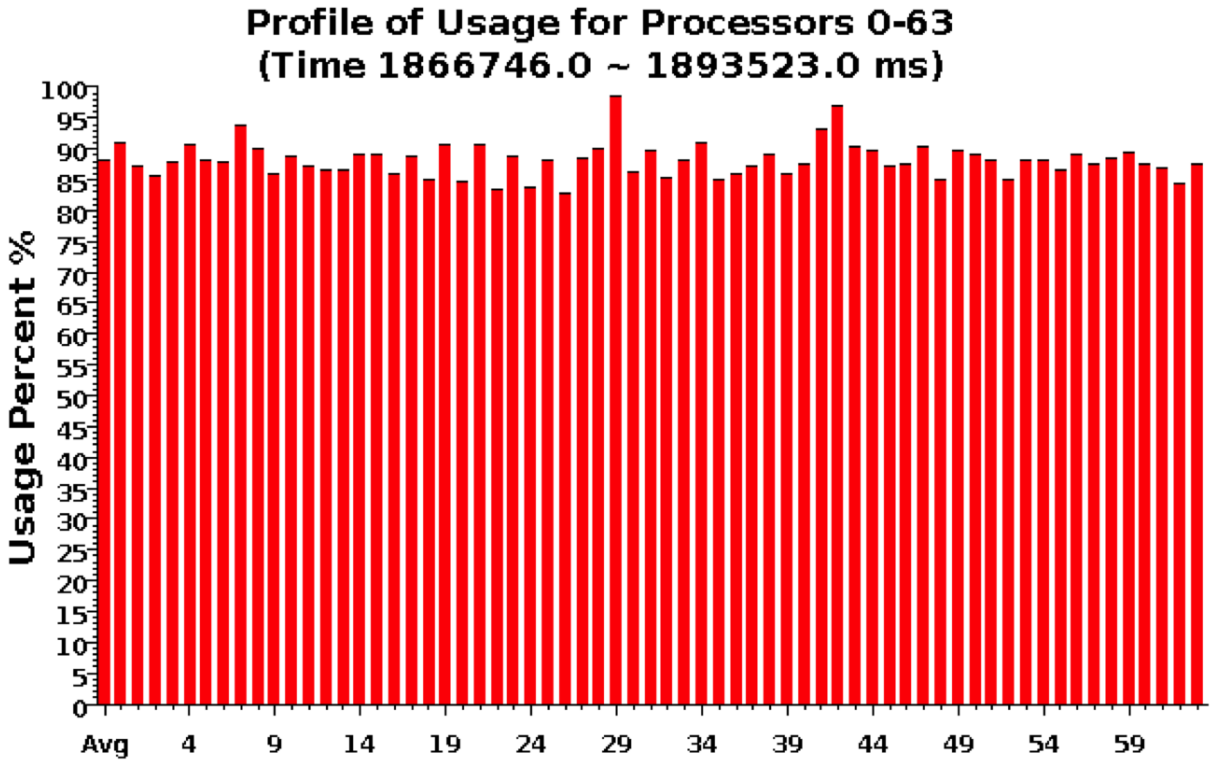
With Load Balancing

1024 objects on 64 processors

- No overdecomposition (64 threads): 4988 sec
- Overdecomposition into 1024 threads: 3713 sec
- Load balancing (1024 threads): 3367 sec



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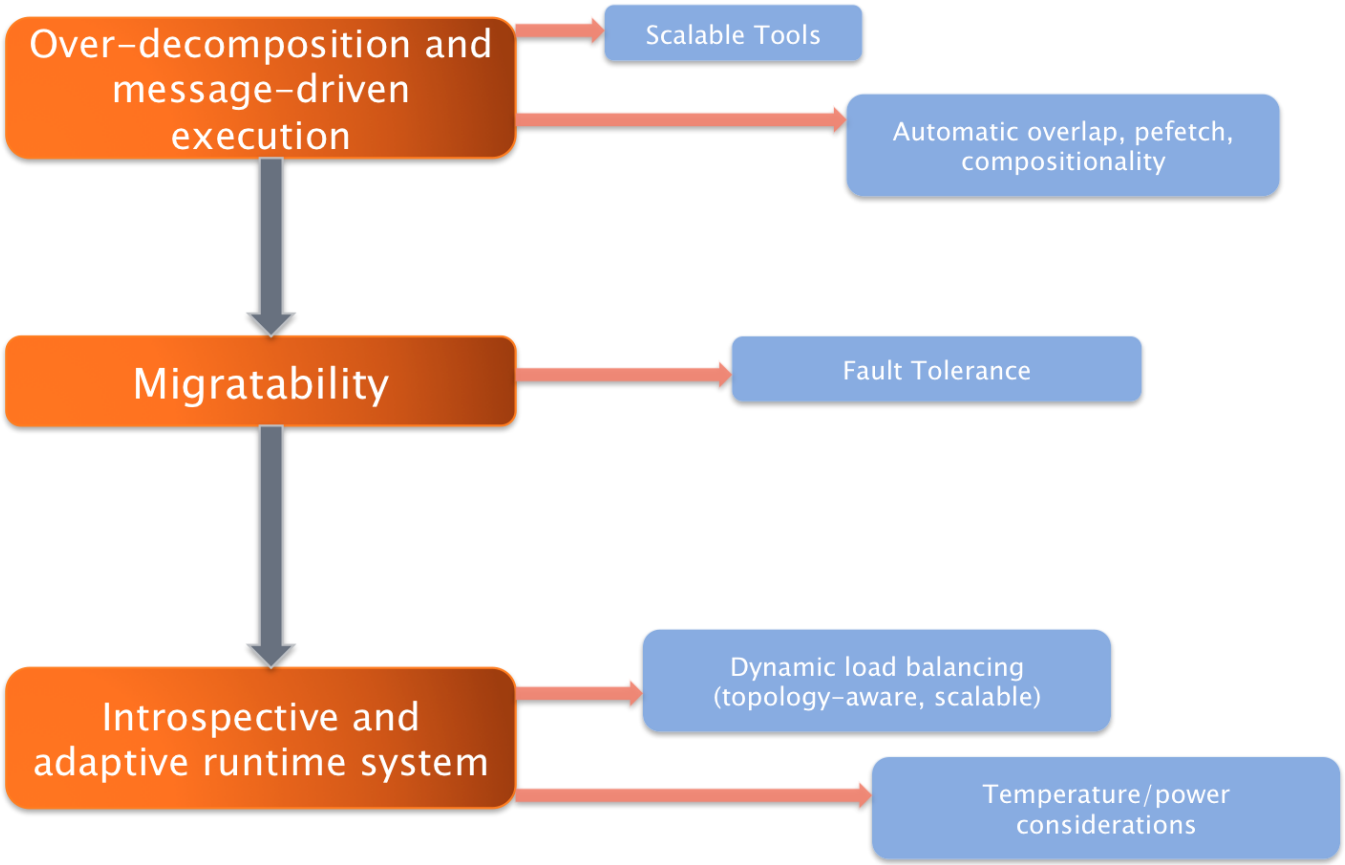
Summary of Benefits



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The Charm++ Programming Language

History

University of Illinois at Urbana-Champaign, early 1990s

Prof. Laxmikant V. Kalé

Prof. Klaus Schulten

Parallel Programming Laboratory (Kalé)

Theoretical and Computational Biophysics Group (Schulten)

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Parallel Programming Galore

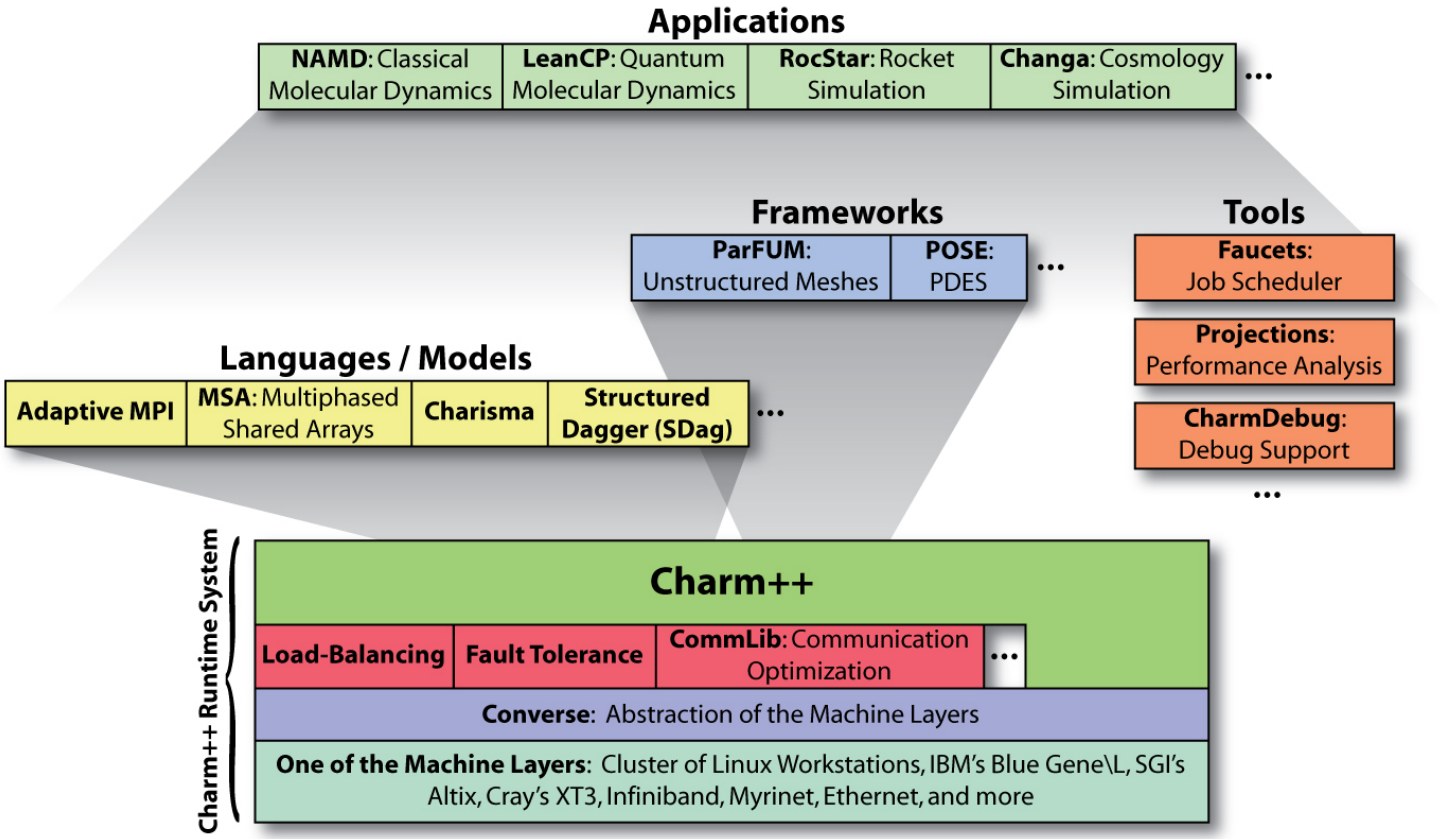
List of Parallel Programming Languages in the 90s

"C* in C	CUMULVS	Java RMI	P-RIO	Quake
ABCPL	DAGGER	javaPG	P3L	Quark
ACE	DAPPLE	JAVAR	P4-Linda	Quick Threads
ACT++	Data Parallel C	JavaSpaces	Pablo	Sage++
ADDAP	DC++	JIDL	PADE	SAM
Adl	DCE++	Joyce	PADRE	SCANDAL
Adsmith	DDD	Karma	Panda	SCHEDULE
AFAPI	DICE	Khoros	Papers	SciTL
ALWAN	DIPC	KOAN/Fortran-S	Para++	SDDA
AM	Distributed Smalltalk	LAM	Paradigm	SHMEM
AMDC	DOLIB	Legion	Parafrase2	SIMPLE
Amoeba	DOME	Lilac	Paralation	Sina
AppLeS	DOSMOS	Linda	Parallaxis	SISAL
ARTS	DRL	LiPS	Parallel Haskell	SMI
Athapascan-0b	DSM-Threads	Locust	Parallel-C++	SONiC
Aurora	Ease	Lparx	ParC	Split-C
Automap	ECO	Lucid	ParLib++	SR
bb_threads	Eiffel	Maisie	ParLin	Sthreads
Blaze	Emerald	Manifold	Parlog	Strand
BlockComm	EPL	Mentat	Parmacs	SUIF
BSP	Excalibur	Meta Chaos	Parti	SuperPascal
C*	Express	Midway	pC	Synergy
C**	Falcon	Millipede	pC++	TCGMSG
C4	Filaments	Mirage	PCN	Telegraphos
CarlOS	FLASH	Modula-2*	PCP:	The FORCE
Cashmere	FM	Modula-P	PCU	Threads.h++
CC++	Fork	MOSIX	PEACE	TRAPPER
Charlotte	Fortran-M	MpC	PENNY	TreadMarks
Charm	FX	MPC++	PET	UC
Charm++	GA	MPI	PETSc	uC++
Chu	GAMMA	Multipol	PH	UNITY
Cid	Glenda	Munin	Phosphorus	V
Cilk	GLU	Nano-Threads	POET	ViC*
CM-Fortran	GUARD	NESL	Polaris	Visifold V-NUS
Code	HAsL	NetClasses++	POOL-T	VPE
Concurrent ML	HORUS	Nexus	POOMA	Win32 threads
Converse	HPC	Nimrod	POSYBL	WinPar
COOL	HPC++	NOW	PRESTO	WWWinda
CORRELATE	HPF	Objective Linda	Prospero	XENOOPS
CparPar	IMPACT	Occam	Proteus	XPC
CPS	ISETL-Linda	Omega	PSDM	Zounds
CRL	ISIS	OOF90	PSI	ZPL
CSP	JADA	Orca	PVM	
Cthreads	JADE	P++	QPC++	

"Patterns for Parallel Programming" (Tim Mattson, et al, 2004)

Charm++ Runtime System

A whole programming ecosystem



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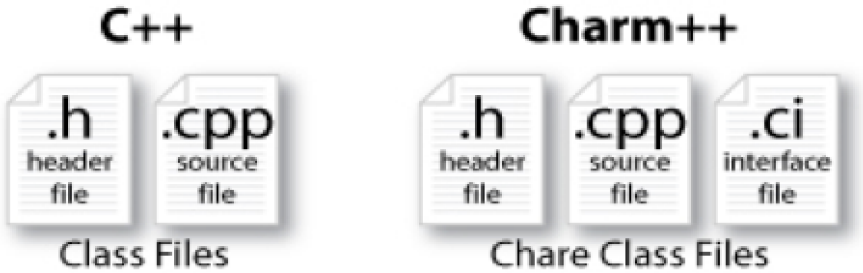
Charm++ File Structure

Header, source, and interface files

- C++ objects (including Charm++ objects)
  - Defined in regular `.h` and `.C` files
- Chare objects, entry methods (asynchronous methods)
  - Defined in `.ci` file
  - Implemented in the `.C` file



Charm Interface

Modules

- Charm++ programs are organized as a collection of modules
- Each module has one or more chares
- The module that contains the *mainchare*, is declared as the `mainmodule`
- Each module, when compiled, generates two files: `MyModule.decl.h` and `MyModule.def.h`

`.ci file`

```
[main]module MyModule {
  //... chare definitions ...
};
```

Charm Interface

Chares

- Chares are parallel objects that are managed by the RTS
- Each chare has a set *entry methods*, which are asynchronous methods that may be invoked remotely
- The following code, when compiled, generates a C++ class `CBase_MyChare` that encapsulates the RTS object
- This generated class is extended and implemented in the `.C` file

`.ci file`

```
[main]chare MyChare {
  //... entry method definitions ...
};
```

`.C file`

```
class MyChare : public CBase_MyChare {
  //... entry method implementations ...
};
```

Charm Interface

Entry methods

- Entry methods are C++ methods that can be remotely and asynchronously invoked by another chare

`.ci` file:

```
entry MyChare(); /* constructor entry method */
entry void foo();
entry void bar(int param);
```

`.C` file:

```
MyChare::MyChare() { /*... constructor code ...*/ }

MyChare::foo() { /*... code to execute ...*/ }

MyChare::bar(int param) { /*... code to execute ...*/ }
```

Charm Interface

`mainchare`

- Execution begins with the `mainchare`'s constructor
- The `mainchare`'s constructor takes a pointer to system-defined class `CkArgMsg`
- `CkArgMsg` contains `argv` and `argc`
- The `mainchare` will typically create some additional chares

Creating a Chare

Interacting object on a distributed system

- A chare declared as `chare MyChare {...};` can be instantiated by the following call:

```
CProxy_MyChare::ckNew(... constructor arguments ...);
```

- To communicate with this class in the future, a *proxy* to it must be retained

```
CProxy_MyChare proxy =
  CProxy_MyChare::ckNew(... constructor arguments ...);
```

Chare Proxies

Representative of a real object

- A chare's own proxy can be obtained through a special variable `thisProxy`
- Chare proxies can also be passed so chares can learn about others
- In this snippet, `MyChare` learns about a chare instance `main`, and then invokes a method on it:

`.ci` file

```
entry void foobar2(CProxy_Main main);
```

`.C` file

```
MyChare::foobar2(CProxy_Main main) {
  main.foo();
}
```

Charm++ Termination

More than finishing execution

- There is a special system call `CkExit()` that terminates the parallel execution on all processors (but it is called on one processor) and performs the required cleanup
- The traditional `exit()` is insufficient because it only terminates one process, not the entire parallel job (and will cause a hang)
- `CkExit()` should be called when you can safely terminate the application (you may want to synchronize before calling this)

Example

Chare creation, `.ci` file

```
mainmodule MyModule {
  mainchare Main {
    entry Main(CkArgMsg *m);
  };

  chare Simple {
    entry Simple(int x, double y);
  };
};
```

Example

Chare creation, .C file

```
#include <stdio.h>
#include "MyModule.decl.h"

class Main : public CBase_Main {
public: Main(CkArgMsg* m) {
    ckout << "Hello World!" << endl;
    if (m->argc > 1) ckout << " Hello " << m->argv[1] << "!!!"
        << endl;
    double pi = 3.1415;
    CProxy_Simple::ckNew(12, pi);
  };
};
class Simple : public CBase_Simple {
public: Simple(int x, double y) {
   ckout << "Hello from a simple chare running on " << CkMyPe()
       << endl;
   ckout << "Area of a circle of radius" << x << " is " << y*x*x
       << endl;
   CkExit();
 }
};

#include "MyModule.def.h"
```

Asynchronous Methods

Beyond two-sided communication

- Entry methods are invoked by performing a C++ method call on a chare's proxy

```
CProxy_MyChare proxy =
  CProxy_MyChare::ckNew(... constructor arguments ...);

proxy.foo();
proxy.bar(5);
```

- The `foo` and `bar` methods will then be executed with the arguments, wherever the created chare, `MyChare`, happens to live
- The policy is one-at-a-time scheduling (that is, one entry method on one chare executes on a processor at a time)

Asynchronous Methods

Beyond FIFO channels

- Method invocation is not ordered (between chares, entry methods on one chare, etc.)
- For example, if a chare executes this code:

```
CProxy_MyChare proxy = CProxy_MyChare::ckNew();
proxy.foo();
proxy.bar(5);
```

- These prints may occur in **any** order

```
MyChare::foo() {
  ckout << "foo executes" << endl;
}

MyChare::bar(int param) {
  ckout << "bar executes with " << param << endl;
}
```

Example

Asynchronous methods

- For example, if a chare invokes the same entry method twice:

```
proxy.bar(7);
proxy.bar(5);
```

- These may be delivered in **any** order

```
MyChare::bar(int param) {
  ckout << "bar executes with " << param << endl;
}
```

- Output

```
bar executes with 5
bar executes with 7
```

OR

```
bar executes with 7
bar executes with 5
```

Example

Asynchronous `.ci` file

```
mainmodule MyModule {
  mainchare Main {
    entry Main(CkArgMsg *m);
  };
  chare Simple {
    entry Simple(double y);
    entry void findArea(int radius, bool done);
  };
};
```

Exercise 1.3

Does this program execute correctly?

```
struct Main : public CBase_Main {
  Main(CkArgMsg* m) {
    double pi = 3.1415;
    CProxy_Simple sim = CProxy_Simple::ckNew(pi);
    for (int i = 1; i< 10; i++) sim.findArea(i, false);
    sim.findArea(10, true);
  };
};

struct Simple : public CBase_Simple {
 float y;
 Simple(double pi) {
   y = pi;
   ckout << "Hello from a simple chare running on " << CkMyPe()
         << endl;
 }
 void findArea(int r, bool done) {
   ckout << "Area of a circle of radius" << r << " is " << y*r*r <<
         endl;
   if (done) CkExit();
 }
};
```

Data Types and Entry Methods

STL supported

- You can pass basic C++ types to entry methods (`int`, `char`, `bool`, etc.)
- C++ STL data structures can be passed by including `pup_stl.h`
- Arrays of basic data types can also be passed like this:
- `.ci` file:

```
entry void foobar(int length, int data[length]);
```

- `.C` file:

```
MyChare::foobar(int length, int* data) {
  // ... foobar code ...
}
```

Readonlys

Constants on a distributed system

- A *readonly* is a global (within a module) read-only variable that can only be written to in the `mainchare`'s constructor
- Can then be read (**not written!**) by any chare in the module
- It is declared in the `.ci` file:

```
readonly <type> <name>;
readonly CProxy_Main mainProxy;
readonly int numChares;
```

- And defined the the `.C` file:

```
<type> <name>;
CProxy_Main mainProxy;
int numChares;
```

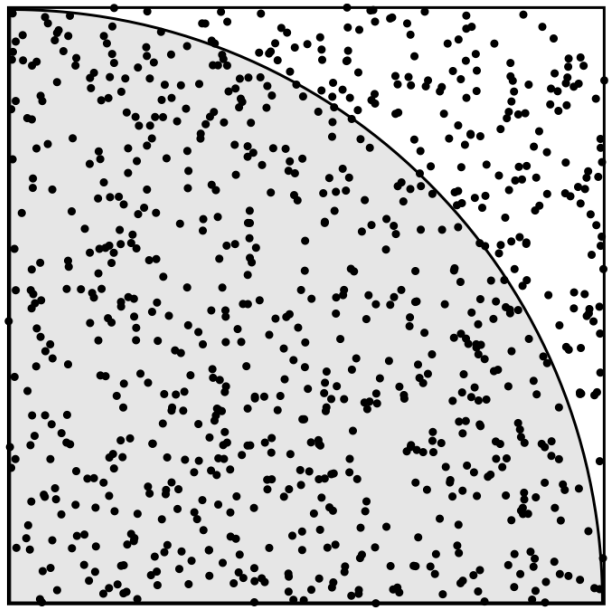
- And set in the `mainchare`'s constructor

```
MyChare::MyChare(CkArgMsg *m) {
  mainProxy = thisProxy;
  numChares = 10;
}
```

Exercise 1.4

Computing π

Use a Monte Carlo method to compute π:



Complete the code in directory:

`code/pi/skeleton`

of the class repository:

```
git clone https://github.com/emenesesrojas/parallel_objects.git
```

Do not forget to define variable `CHARMDIR` in the Makefile

Collections of Objects

Concepts

- Objects can be grouped into indexed collections
- Basic examples
  - Matrix block
  - Chunk of unstructured mesh
  - Portion of distributed data structure
  - Volume of simulation space
- Advanced examples
  - Abstract portions of computation
  - Interactions among basic objects or underlying entities

Collections of Objects

Types of collections

- Structured: 1D, 2D, . . . , 6D
- Unstructured: anything hashable
- Dense
- Sparse
- Static - all created at once
- Dynamic - elements come and go

Example

Chare Array Hello World

```
mainmodule arr {


  mainchare Main {
    entry Main(CkArgMsg*);
  }

  array [1D] hello {
    entry hello(int);
    entry void printHello();
  }
}
```

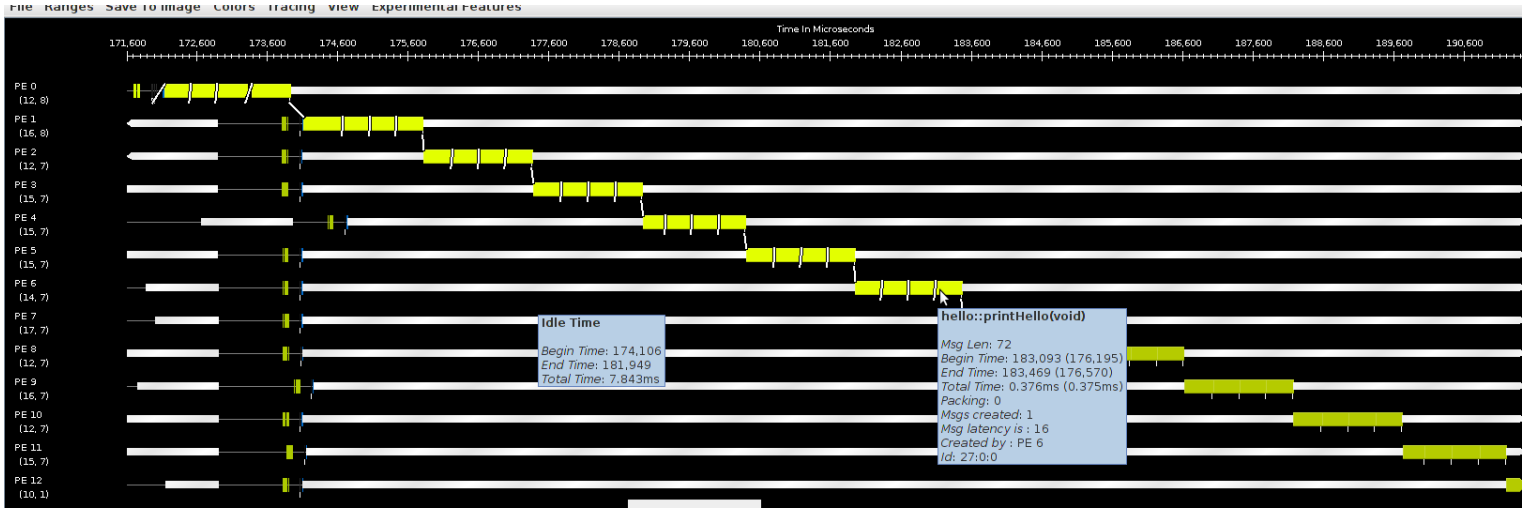
Example

Chare array Hello World

```
#include "arr.decl.h"

struct Main : CBase_Main {
  Main(CkArgMsg* msg) {
    int arraySize = atoi(msg->argv[1]);
    CProxy_hello p = CProxy_hello::ckNew(arraySize, arraySize);
    p[0].printHello();
  }
};

struct hello : CBase_hello {
  hello(int n) : arraySize(n) { }
  hello(CkMigrateMessage*) { }
  void printHello() {
    CkPrintf("PE[%d]: hello from p[%d]\n", CkMyPe(), thisIndex);
    if (thisIndex == arraySize - 1) CkExit();
    else thisProxy[thisIndex + 1].printHello();
  }
  private:
  int arraySize;
};

#include "arr.def.h"
```

Example

Hello World array Projections timeline view



Run on BG/Q 16 Nodes, mode c16, 1024 elements (4 per process)

Declaring a Chare Array

Dimensionality and functionality

`.ci` file:

```
array [1d] foo {
  entry foo(); // constructor
  // ... entry methods ...
}
array [2d] bar {
  entry bar(); // constructor
  // ... entry methods ...
}
```

`.C` file:

```
struct foo : public CBase_foo {
  foo() { }
  foo(CkMigrateMessage*) { }
  // ... entry methods ...
};
struct bar : public CBase_bar {
  bar() { }
  bar(CkMigrateMessage*) { }
  // ... entry methods ...
};
```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Constructing a Chare Array

Elements are distributed on nodes of the system

- Constructed much like a regular chare
- The size of each dimension is passed to the constructor

```
void someMethod() {
    CProxy_foo::ckNew(10);
    CProxy_bar::ckNew(5, 5);
}
```

- The proxy may be retained:

```
CProxy_foo myFoo = CProxy_foo::ckNew(10);
```

- The proxy represents the entire array, and may be indexed to obtain a proxy to an individual element in the array

```
myFoo[4].invokeEntry();
```

thisIndex

Pretty much like this

- 1d: `thisIndex` returns the index of the current chare array element
- 2d: `thisIndex.x` and `thisIndex.y` returns the indices of the current chare array element

.ci file:

```
array [1d] foo {
  entry foo();
}
```

.C file:

```
struct foo : public CBase_foo {
  foo() {
    CkPrintf("array index = %d", thisIndex);
  }
};
```

Collections of Objects

Runtime service

- System knows how to 'find' objects efficiently: $(\textit{collection}, \textit{index}) \rightarrow \textit{processor}$
- Applications can specify a mapping, or use simple runtime-provided options (e.g. blocked, round-robin)
- Distribution can be static, or dynamic
- Key abstraction: application logic doesn't change, even though performance might

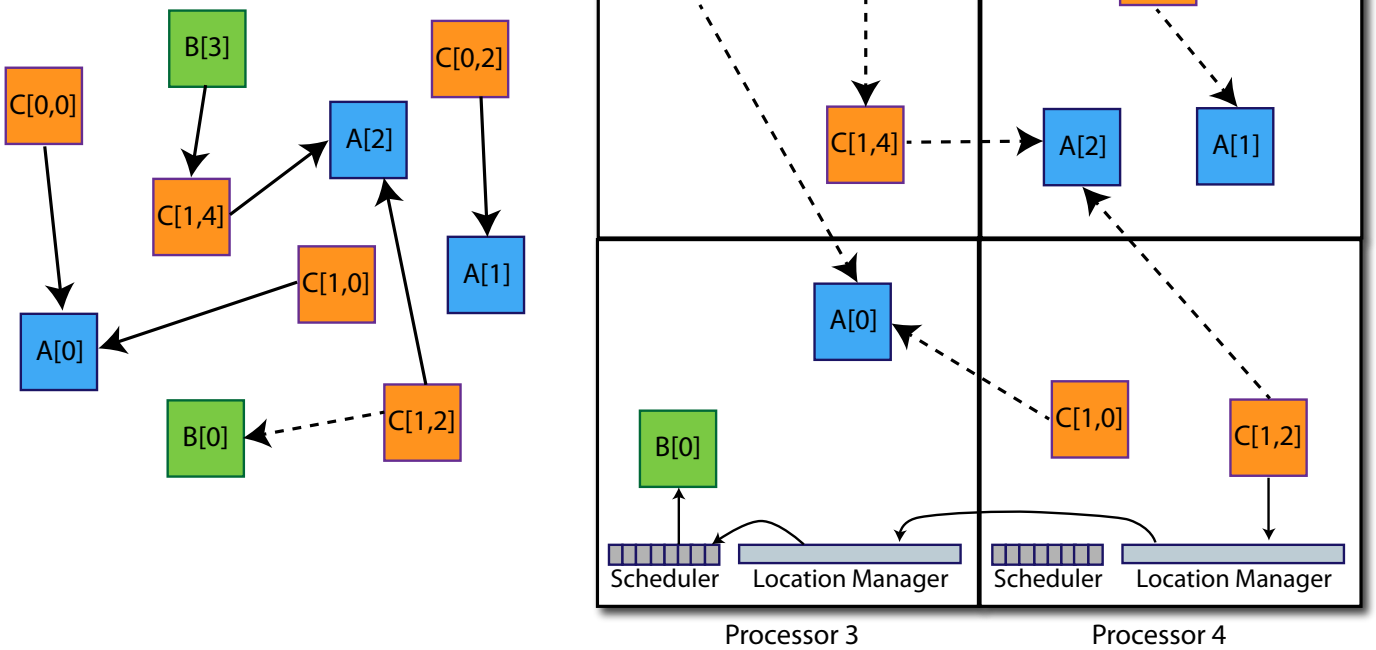
Collections of Objects

Runtime service

- Can develop and test logic in objects separately from their distribution
- Separation in time: make it work, then make it fast
- Division of labor: domain specialist writes object code, computationalist writes mapping
- Portability: different mappings for different systems, scales, or configurations
- Shared progress: improved mapping techniques can benefit existing code

Collections of Objects

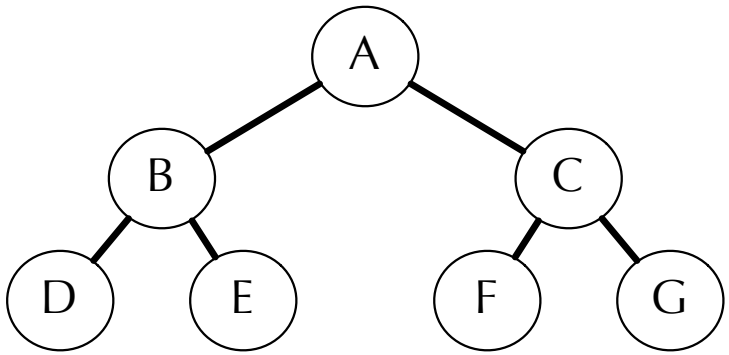
Interacting collections



Collective Communication Operations

Efficiency and expressivity

- Point-to-point operations involve only two objects
- Collective operations that involve a collection of objects
- Broadcast: calls a method in each object of the array
- Reduction: collects a contribution from each object of the array
- A spanning tree is used to send/receive data



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Broadcast

One-to-many

- A message to each object in a collection
- The chare array proxy object is used to perform a broadcast
- It looks like a function call to the proxy object
- From the main chare:

```
CProxy_Hello helloArray = CProxy_Hello::ckNew(helloArraySize);
helloArray.foo();
```

- From a chare array element that is a member of the same array:

```
thisProxy.foo()
```

- From any chare that has a proxy p to the chare array

```
p.foo()
```

Reduction

Many-to-one

- Combines a set of values: sum, max, aggregate
- Usually reduces the set of values to a single value
- Combination of values requires an operator
- The operator must be commutative and associative
- Each object calls `contribute` in a reduction

Example

Reduction

```
mainmodule reduction {
  mainchare Main {
    entry Main(CkArgMsg* msg);
    entry [reductiontarget] void done(int value);
  };
  array [1D] Elem {
    entry Elem(CProxy_Main mProxy);
  };
}
```

Example

Reduction

```
#include "reduction.decl.h"

const int numElements = 49;

class Main : public CBase_Main {
public:
  Main(CkArgMsg* msg) { CProxy_Elem::ckNew(thisProxy, numElements); }
  void done(int value) {
    CkAssert(value == numElements * (numElements - 1) / 2);
    CkPrintf("value: %d\n", value);
    CkExit();
  }
};

class Elem : public CBase_Elem {
public:
  Elem(CProxy_Main mProxy) {
    int val = thisIndex;
    CkCallback cb(CkReductionTarget(Main, done), mProxy);
    contribute(sizeof(int), &val, CkReduction::sum_int, cb);
  }
  Elem(CkMigrateMessage*) { }
};

#include "reduction.def.h"
```

Output:

```
value: 1176
Program finished.
```

Exercise 1.5

Key-value store

Implement a key-value store using a 1D chare array:

Key	Value
K1	AAA,BBB,CCC
K2	AAA,BBB
K3	AAA,DDD
K4	AAA,2,01/01/2015
K5	3,ZZZ,5623

Complete the code in directory:

`code/keyvalue/skeleton`

of the class repository:

```
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```

Do not forget to define variable `CHARMDIR` in the Makefile

Concluding Remarks

- Parallel objects bring about a modular and composable parallel programming framework
- Two major benefits of over-decomposition are:
  - Overlap of communication and computation
  - Load balancing
- Chare arrays are the main object collection in Charm++

Thank You!
Q&A