Concurrent Collections (CnC)

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Outline

• Intro to the CnC
• Tuning CnC
• CnC for distributed memory
Outline

• Intro to the CnC
• Tuning CnC
• CnC for distributed memory
The Big Idea

• Don’t think about what operations can run in parallel
  – *Difficult and depends on target*

• Think about the semantic ordering constraints only
  – *Easier and depends only on application*
Exactly Two Sources Of Ordering Requirements

- Producer must execute before consumer

Producer - consumer

- **step1** → **item** → **step2**
Exactly Two Sources Of Ordering Requirements

- Producer must execute before consumer
- Controller must execute before controllee

Diagram:
- **Producer - consumer**
  - Compute Step: step1
  - Data Item: item
  - Compute Step: step2

- **Controller - controllee**
  - Compute Step: step1
  - Control Tag: tony
  - Compute Step: step2
Cholesky factorization
Cholesky factorization
# Cholesky factorization

<table>
<thead>
<tr>
<th>Cholesky</th>
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</thead>
<tbody>
<tr>
<td>Trisolve</td>
<td></td>
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</table>

Arrow pointing down from Cholesky to Trisolve.
**Cholesky factorization**

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Slightly simplified
Cholesky factorization
4 simple steps to a CnC application
1: The white board level

- Data
- Computations
- Producer/consumer relations among them
- I/O
2: Distinguish among the instances

- Distinct instances (chunks of data or computation) may be distinctly scheduled and mapped

- A collection is a statically named set of dynamic instances
2: Distinguish among the instances

- Distinct instances (chunks of data or computation) may be distinctly scheduled and mapped.
- A collection is a statically named set of dynamic instances.
- Optional: tag functions relating the tags, e.g., Cholesky: \textit{iter} $\rightarrow$ Array: \textit{iter}, \textit{iter}, \textit{iter}.
Control tag

• Tuple – unique identifier
  – <row, col, iteration>
  – <socialSecurityNumber, date>
  – <treeNode>

• Meaning of control relationship
  – For each row/col/iteration tuple in the collection Ceasar, the corresponding instance of foo will execute sometime.
  – An instance of foo has access to the values of row, col and iteration.

• Control dependence and data dependence are on the same footing
3: What are the control tag collections

- **Control Tag**
  - CholeskyTag: iter

- **Compute Step**
  - Cholesky: iter

- **Control Tag**
  - TrisolveTag: row, iter

- **Compute Step**
  - Trisolve: row, iter

- **Control Tag**
  - UpdateTag: col, row, iter

- **Compute Step**
  - Update: col, row, iter

- **Data Item**
  - Array: col, row, iter
4: Who produces control

- **CONTROL TAG**
  - CholeskyTag: iter

- **COMPUTE STEP**
  - Cholesky: iter
  - TrisolveTag: row, iter
  - Trisolve: row, iter
  - UpdateTag: col, row, iter
  - Update: col, row, iter

- **DATA ITEM**
  - Array: col, row, iter
Actual app: cell tracker
Sample step (cholesky)

```cpp
// Perform unblocked Cholesky factorization on the input block
// Output is a lower triangular matrix.
int cholesky::execute( const int & t, cholesky_context & c ) const
{
    tile_const_ptr_type A_block;
    tile_ptr_type L_block;
    int b = c.b;
    const int iter = t;

    c.Array.get(triple(iter,col,row), A_block); // Get the input tile.
    L_block = std::make_shared< tile_type >( b ); // allocate output tile
    for(int k_b = 0; k_b < b; k_b++) {
        // do all the math on this tile
    }
    c.Array.put(triple(iter+1,col,row), L_block); // Write the output tile
    return CnC::CNC_Success;
}
```

**Steps have no side-effects**
**Steps are atomic**
**Items are dynamic single assignment**
**Spike Performance**

James Brodman - UIUC, Intel

- Parallel solver for banded linear systems of equations
- Complex algorithm but “easily” maps onto CnC
- Same code for shared and distributed memory

**Runtime (S)**

- MKL
- MKL + OMP
- HTA (TBB)
- CnC
- HTA (MPI)
- DistCnC

**Shared memory**

1048576 w/ 128 Super/Sub Diagonals, 32 partitions

**Shared/distributed memory**

(4 nodes, GigE)
Spike Performance
James Brodman - UIUC, Intel

Shared memory

- Parallel solver for banded linear systems of equations
- Complex algorithm but "easily" maps onto CnC
- Same code for shared and distributed memory

High level does not imply poor performance

Shared/distributed memory
(4 nodes, GigE)

- 1048576 w/ 128 Super/Sub Diagonals, 32 partitions
Semantics of CnC

- Semantics defined in terms of attributes of instances.

- The current state is described by the current set of instances and their attributes.
CnC is a coordination language: paired with a computation language

- **Existing:**
  - C++ (intel)
  - Java (Rice)
  - Haskell (Indiana)
  - Python (Rice)
  - Scala (Rice)
  - APL (Indiana)

- **In the works:**
  - Fortran (Rice)
  - Chapel (UIUC)

- **Next up:**
  - Matlab (Rice)

Rice = Vivek Sarkar’s group
Indiana = Ryan Newton’s group
UIUC = David Padua’s group
CnC is a high level model allows for a wide variety of runtime approaches

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<thead>
<tr>
<th></th>
<th>grain</th>
<th>distribution</th>
<th>schedule</th>
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<tr>
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Possible expressions of the model

• Graphical interface

• Textual representation
  – Rice version
  – previous Intel versions

• API
  – Current Intel release
Key properties

• Think about the meaning of your program
  – Not about parallelism
• Deterministic & serializable
  – Easy to debug
• Separation of concerns simplifies everything
  – Computation from coordination
  – Domain spec from tuning spec
    • Domain spec is free of tuning and largely independent of architecture
• Unified programming for shared and distributed memory
  – Not like MPI/OpenMP combo
Intel® Concurrent Collections for C++

- New whatif-release
  - Header-files, shared libs
  - Samples
  - Documentation
    - CnC concepts
    - Using CnC
    - Tutorials

- Template library with runtime
  - For Windows(IA-32/Intel-64) and Linux (Intel-64)
  - Shared and distributed memory
Outline

• Intro to the CnC
• Tuning CnC
• CnC for distributed memory
Tuning expert
with Rice: Mike Burke, Sanjay Chatterjee, Zoran Budimlic

• Without tuning
  – Very good performance
  – Typically more than enough parallelism
  – Asynchronous execution

• Multiple tuning specs for each domain spec
  – Tuning spec is in addition and separate
  – Semantic constraints from the domain spec are still requirements
  – A tuned execution is a one of the many legal executions of the domain spec. Goal: guide away from bad ones.
Foundation for tuning: Hierarchical Affinity groups

• Affinity groups
  – Avoid mappings with poor locality (temporal + spatial)
    – No benefit if too far away in either time or space
    – Foundation doesn’t distinguish space from time
    – On top of this foundation we allow (but don’t require) time-specific and space-specific control

• Hierarchy
  – Same low-level group => tight affinity
  – Same higher-level group => weaker affinity
Cholesky domain spec

CONTROL TAG
CholeskyTag: iter

COMPUTE STEP
Cholesky: iter

CONTROL TAG
TrisolveTag: row, iter

COMPUTE STEP
Trisolve: row, iter

CONTROL TAG
UpdateTag: col, row, iter

COMPUTE STEP
Update: col, row, iter

DATA ITEM
Array: col, row, iter
Hierarchical affinity structure

**COMPUTE STEP**

*Cholesky:*

**COMPUTE STEP**

*Trisolve:*

**COMPUTE STEP**

*Update:*
Hierarchical affinity groups have names

Affinity Group: GroupC:
- Compute Step: Cholesky

Affinity Group: GroupTU:
- Compute Step: Trisolve
- Compute Step: Update
We distinguish among instances of affinity groups
Specify the instances of each affinity group

**CONTROL TAG**
CholeskyTag: iter

**AFFINITY GROUP**
GroupC: iter

**COMPUTE STEP**
Cholesky: iter

**CONTROL TAG**
TrisolveTag: row, iter

**AFFINITY GROUP**
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**COMPUTE STEP**
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**COMPUTE STEP**
Update: col, row, iter
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Space-specific mappings

- **CONTROL TAG**
  - CholeskyTag: iter

- **AFFINITY GROUP**
  - **GroupC**: iter
    - **COMPUTE STEP**
      - Cholesky: iter
    - **CONTROL TAG**
      - TrisolveTag: row, iter

- **AFFINITY GROUP**
  - **GroupTU**: row, iter
    - **COMPUTE STEP**
      - Trisolve: row, iter
    - **COMPUTE STEP**
      - Update: col, row, iter

- Replicate components of this group across sockets
- Distribute components of this group across nodes
- Distribute components of this group across nodes via func()
Time-specific mappings

Relative time among components within a group.

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<thead>
<tr>
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<td>serial/barrier</td>
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</tr>
<tr>
<td>overlapping</td>
<td>priority</td>
<td>arbitrary</td>
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Space-time combinations

{big_memory_footprint: i}

Distribute across address spaces (space)
Within each address space exclusive (time)

{video_processing: frameID}

cyclic distribution among address spaces (space)
ordered & overlapping within address spaces (time)
Related work

• Control of time
  – Various types of parallelism
    Data parallel, task parallel, streaming, fork-join, ...

• Control of space
  – Support for distributions
    Hierarchical Place Trees, HPF, ...

CnC can control both time and space and in a unified way
We allow (but don’t require) the tuning expert to blur the distinction between them

Knobe & Burke “Tuning Language for Concurrent Collections”
Compilers for Parallel Computing (CPC 2012)
Outline

• Intro to the CnC
• Tuning CnC
• CnC for distributed memory
Distributed CnC
Intel: Frank Schlimbach

• CnC is a declarative and high level model
  – Abstracts from memory model

• Provides a unified programming model for shared and distributed memory
  – Same binary runs on both
  – Easy to switch between shared and distributed memory
    (no explicit message passing needed)

• **CnC comes with a control methodology**
  – Allows controlling work distribution

• **CnC comes with a data methodology**
  – Provides hooks for selective data distribution
Limitations of distributed computing apply

• Usual caveats for distributed memory apply
  – E.g. ratio between data-exchange and computation

• Different algorithms might be needed for distributed or shared memory
  – Programming methodology and framework stays the same in any case
  – Over a wide class of applications the algorithm stays the same
Scalability and efficiency: Spike

Scalability

Parallel Efficiency

(matrix: 10Mx10M, 257 bands)
Distributed CnC: without tuning (UTS)

- Unbalanced tree search
  - Tree shape unknown
- CnC code is trivial
  - CnC: 151 loc
  - Shmem: ~1000 loc
  - MPI: ~800 loc
- Performance gap in the middle region is a load-balancing issue
  - Used scheduler available on our release
  - Solved by different scheduler

UTS [T3XXL] Speedup

![Speedup graph showing performance comparison between MPI and CnC across different thread and node configurations.](image-url)
Untuned performance often bad: tuning

**CnC Time (untuned)**

- GigE

**CnC Time (tuned)**

- IB

### Graph Details

- **X-axis:** #nodes (24 h-threads each)
- **Y-axis:** Time [sec]
- **Legend:**
  - red: inverse
  - grey: primes
  - black: mandelbrot
  - green: cholesky

**Software and Services Group**

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CnC tuning easy and efficient

• The general default distribution of steps
  – Data is sent to where needed (requested)
  – Not always efficient

• Tuner can declare functions
  – `consumed_by`: Which steps use this data item (semantics)
  – `compute_on`: Where the step will execute (tuning)
  – To redistribute, modify `compute_on`:
    data items and steps automatically adjusted

• Mapping tag->rank can be computed
  – Compile time
  – Initialization time
  – Execution time
Distribution functions

**Cyclic - Simple**

```cpp
int tuner::compute_on( const int & i ) const
{
    return i % numProcs();
}
```

**Blocked - Minimizes data transfer**

```cpp
int tuner::compute_on( const int & x, y, z ) const
{
    return x * NBLOCKS_X / nx
        + ( y * NBLOCKS_Y / ny ) * nx
        + ( z * NBLOCKS_Z / nz ) * nx * ny
}
```

**Blocked cyclic – Block size/shape is relevant**

```cpp
int tuner::compute_on( int x, y ) const
{
    return ((x + y * m_nx) / BLOCKSIZE) % numProcs();
}
```
Scalability and efficiency: stencil

3D 25-point stencil reads from 2 previous time-steps
Shmem performance similar to cache-oblivious algorithms

Efficiency stays above 97%!
Distribution function for tree

At certain tree-depth stop distributing and stay local

Used for quickSort
Summary

- **Separation of concerns**
  - Computation from coordination
  - Domain spec from tuning spec

- **Domain spec**
  - High-level: hides all the difficulties of low-level techniques
  - Exposes potential parallelism
  - Easy to debug (deterministic)
  - Efficient even with no tuning

- **Tuning spec**
  - Isolated
  - Simple
  - Flexible

- **Support for distributed memory**
  - Distribution is easy because the domain spec already identifies chunks of work and data.
  - Same spec runs on shared and/or distributed memory
  - Distribution functions: isolated to support easy experimentation
Status

• General
  – Available
  – Yearly workshops
  – Used in some intro programming classes as a gentle introduction to parallelism

• Domain language
  – Very good performance on shared memory even without tuning language
    • Bunch of benchmarks
    • Comparable performance to other tools

• Tuning language
  – Ubiquitous High Performance Computing (UPHC)
    • Vivek Sarkar’s group at Rice is currently implementing the tuning language for CnC.

• Distributed CnC
  – Available
  – Next: static analysis to generate distribution functions
New Intel CnC release:

New Intel CnC Yahoo Group:
http://tech.groups.yahoo.com/group/intel_concurrent_collections/

Rice CnC:
http://habanero.rice.edu/cnc

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