Outline

• Sequoia Summary
• Other Cell programming tools
• Sequoia runtime and compilation

Sequoia part courtesy Kayvon Fatahalian, Stanford

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Cell Broadband Engine™ Sony Corp.

Emerging Themes

• Writing high-performance code amounts to...
  - Intelligently structuring algorithms
    [compiler help unlikely]
  - Efficiently using communication
  - Efficiently using parallel resources
    [compilers struggle without help]
  - Generating efficient inner loops (kernels)
    [compilers coming around]

Sequoia

• Language: stream programming for machines with deep memory hierarchies
• Idea: Expose abstract memory hierarchy to programmer
• Implementation: language, compiler, tuner, and runtime
  - benchmarks run well on Cell processor based systems, clusters of PCs, SMPs, out-of-core computation, and combinations of above

Sequoia’s method

• Explicit communication between abstract memories
• Locality awareness
• Hierarchy portability
  - Across machines, within levels of a machine
• Programmer expresses combined computation and decomposition parameterized algorithm
  - System follows algorithm to map to a specific machine

Sequoia summary

• Problem:
  - Deep memory hierarchies pose perf. programming challenge
    - Memory hierarchy different for different machines
• Solution: Abstract hierarchical memory in programming model
  - Program the memory hierarchy explicitly
    - Expose properties that affect performance
• Approach: Express hierarchies of tasks
  - Execute in local address space
  - Call-by-value-result semantics exposes communication
  - Parameterized for portability
Sequoia and Cell Programming Challenges

- Sequoia manages threading and synchronization
- Sequoia manages communication and all DMAs
  - Including padding and performance, but not alignment
- Sequoia manages LS
  - Allocation and packing
- Sequoia manages scheduling
  - SWP of mappar to hide communication latency
- Sequoia doesn’t help with SPE code
  - Use low-level compiler tools such as XLC
- Sequoia doesn’t currently help with some memory restrictions
  - Alignment, limited support but cannot rely on Sequoia
  - Banks
  - Sequoia does pad for access granularity restrictions

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Tools From IBM

- Cell SDK 3.0
  - APIs for handling communication, synchronization, and DMA
  - LIBSPU and IPUPS for getting the SPEs to do something and setting up threads and memory
  - Intrinsics for programming the SPE pipeline directly
  - GCC port for PPE and SPE part (separate compiler)
  - XLC port for PPE and SPE part (separate compiler)
  - XLC supposed to optimize for SPE pipeline with branch hints, scheduling, instruction prefetch, ...
  - Automatic SIMD-ization

Tools From Academia

- Sequoia
- Cell Superscalar (CelSs)
  - Program with OpenMP like directives to identify kernels
  - Uses SW cache intensively
  - Runtime applies superscalar style optimization and scheduling to coarse-grained kernels (identified above)
- Charm++
  - Runtime based approach
  - Objects with explicit communication and “entry points” for synchronization
  - Uses a work queue and peaks into it to do the DMAs

Tools From Industry

- Mercury Systems
  - Array based language
  - Highly-tuned BLAS and FFT
- RapidMind
  - Dynamically compiled program
  - Relies on array data types
  - Builds up kernels and DMAs
How this all works (Cell example)

- Back to SGEMM example:
  - User initializes Sequoia and allocates data from their code

```c
main()
{
    sqInit();
    A = sqAlloc2D(...);
    B = sqAlloc2D(...);
    C = sqAlloc2D(...);
    matmul(A,B,C);
    sqShutdown();
}
```

How this all works

- Back to SGEMM example:
  - User initializes Sequoia and allocates data from their code

Top level task call

```c
task matmul::inner (float A[10][10], float B[10][10], inout float C[10][10])
{
    tunable int P, Q, R;
    mappar (int i=0 to M/P, int j=0 to N/R)
    mapseq (int k=0 to T/Q)
    matmul(A[i][j], B[k], C[i][j]);
}
```

Leaf task call

```c
task matmul::inner (float A[10][10], float B[10][10], inout float C[10][10])
{
    tunable int P, Q, R;
    mappar (int i=0 to M/P, int j=0 to N/R)
    mapseq (int k=0 to T/Q)
    matmul(A[i][j], B[k], C[i][j]);
}
```

Allocate data

PPE launches bootstrap threads on SPEs

PPE mails SPE leaf task to instruct olay load and execution

SPE id controls assignment of iteration space and DMA list offsets
Leaf task return

```
task matmul::inner(in float A[M][T], in float B[T][N], inout float C[M][N]) {
    tunable int P, Q, R;
    mappar(int i=0 to M/P, int j=0 to N/R) {
        mapseq(int k=0 to T/Q) {
            matmul(A[P*i:P*(i+1);P][Q*k:Q*(k+1);Q], B[Q*k:Q*(k+1);Q][R*j:R*(j+1);R], C[P*i:P*(i+1);P][R*j:R*(j+1);R]);
        }
    }
}
```

Control return to user code

```
control return to user code
• Back to 5GMM example:
  - User initializes Sequoia and allocates data from their code
  ```
  main() {
    sqInit();...
    A = sqAlloc2D(...);
    B = sqAlloc2D(...);
    C = sqAlloc2D(...);
    ...
    matmul(A,B,C);...
    sqShutdown();
  }
```

Autotuning Sequoia Programs

```
• Autotuner helps user with mapping (user can always override)
```

Specialization with Autotuning

```
• Work by Manman Ren (Stanford), PACT2008
• Use Sequoia to identify what needs tuning
  - Explicit tunables and parameters in the language
• Tuning framework for SW-managed hierarchies
• Automatic profile guided search across tunables
  - Aggressive pruning
  - Illegal parameters (don't fit in memory level)
  - Tunable groups
  - Programmer input on ranges
  - Coarse to fine search
• Loop fusion across multiple loop levels
  - Measure profitability from tunable search
  - Adjust for "tunable mismatch"
  - Realign reuse to reduce communication
```

Overview: mapping the program

```
• Mapped versions are generated
  - Matching the decomposition hierarchy with the machine hierarchy
  - Choosing a variant for each call site
  - Set level of data objects and control statements
```

Explicit SW Management Simplifies Tuning

```
• Smooth search space
• Performance models can also work
  - For Cell, not cluster
```
The search algorithm

- A pyramid search
- A greedy search algorithm at each grid level
  - Achieve good performance quickly due to smoothness of the search space

Start with a coarse grid
Refine the grid when no further progress can be made

Guided Search Converges Quickly

- Smoothness leads to quick convergence

Autotuning Out Performs Programmer

<table>
<thead>
<tr>
<th></th>
<th>CONV2D</th>
<th>SGEMM</th>
<th>FFT3D</th>
<th>SIMD</th>
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</table>

Sequoia compilation

- A compiler for hierarchical bulk operations

1. Is built around the portable abstractions of hierarchical memory and bulk operations.
2. Automatically manages all program data movement to increase memory throughput.
3. Automatically allocates explicitly managed memories.

Compiler for hierarchical bulk operations

We abstract Cell as a tree of memories

- Why a tree of memories?
  - A portable abstraction that matches our target machines of interest: Cell, clusters, etc.
We can model other machines as trees of memories (e.g.) a dual-GPU machine backed by disk storage:

- Not all tree nodes have a processor.
- Leaves of tree are compute-intensive processors.

Modeled machine capabilities:

- 1. Execute out of its local memory.
- 2. Transfer data to/from a child.
- 3. Transfer data to/from its parent.
- 4. Launch code in a child.

Parallelism in the abstract machine model:

- 1. Parallel PEs within a level.
1. Parallel PEs within a level.
2. Concurrent parent/child execution.

Programs comprise four elements

1. Operations (blue).
2. Data (red).
3. Dependences.
Programs comprise four elements

- 1. Operations (green).
- 2. Data (blue).
- 3. Dependencies.

Operations may contain nested subprograms.

Example: SGEMV (matrix x vector)

\[ y = A \cdot x \]
Example: SGEMV (matrix x vector)

Copy(x → x');
Exec(G)

Subprogram G:

Forall(i) {
    Copy(A[i] → A')
    Kernel(A',x' → y')
    Copy(y' → y[i]);
}

Copy A x y x' Exec Forall(i) A' y' Kernel In: x In: A' Out: y'

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Modeled machine capabilities

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3. Transfer data to/from its parent.
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Program IR properties:

1. Is mechanism-independent.
2. Features scalar and bulk operations within a single framework.
3. Spans the entire machine (all levels).
4. Fully captures all program semantics.
5. Exposes parallelism via dependences and “Forall” operations.

Optimizations are IR transformations

• They can be applied at any hierarchy level of the program or the machine.
Optimizations are IR transformations

- They can be applied at any hierarchy level of the program or the machine.
- Correctness: Transformations preserve top-level program inputs and outputs.

Optimization: Copy elimination

- 1. Removing spills [producer-consumer locality].
- 2. Removing duplicates [temporal locality].

Optimization: Copy grouping

Optimization: Exec grouping

Optimization: Hoisting
**Scheduling optimizations**

1. Software pipelining.
2. Competing heuristics:
   1. Maximize operation concurrency.
   2. Group similar operations (e.g., Execs) to amortize issue overheads.

**Optimization: Space allocation**

- Global view of data usage: better than LRU.
- Memory space: Max (240KB)

**Targeting a Cell Processor**
1. Our source-to-source compiler generates two sets of output files.
2. Each Exec operation → SPE overlay.
3. Each Copy operation → DMA command.
   - Data objects and transfers padded to multiples of 16 bytes.
4. DMAs and SPE kernels overlapped where possible.

Summary

- Performance competitive with native code
  - Generic optimization for hierarchical bulk programs
  - Copy elimination
  - DMA transfer coalescing
  - Operation hoisting
  - Array allocation / passing
  - Scheduling (tasks and DMAs)
  - Automatic tuning for performance
- Portable: no source-code changes for different configurations
  - Cell, SMP, Cluster, Disk
  - Compositions of above
  - Automatic tuning
- Maximizes resources (compute or communication)
- Low overhead
### Results - Horizontal portability - GFlop/s

<table>
<thead>
<tr>
<th></th>
<th>Scalar</th>
<th>SMP</th>
<th>Disk</th>
<th>Cluster</th>
<th>Cell</th>
<th>PS3</th>
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<td>CONV2D</td>
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<td>FFT3D</td>
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<td>7.8</td>
<td>0.1</td>
<td>7.5</td>
<td>54</td>
<td>31*</td>
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<tr>
<td>GRAVITY</td>
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<td>68</td>
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<td>71</td>
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<tr>
<td>HAMMER</td>
<td>0.9</td>
<td>11</td>
<td>0.9</td>
<td>12</td>
<td>12</td>
<td>7.1*</td>
</tr>
</tbody>
</table>

* Reduced dataset size to fit in memory

---

### Cell utilization

- **DRAM Utilization:** Sustained BW, as percentage of available peak
- **SPE Utilization:** Percentage of time the SPEs are running at a steady rate

### 2 Level Utilization

- Idle waiting on Xfer (M1-M0)
- Runtime Overhead (M1-M0)
- Leaf task execution (M0)

### Composed systems utilization

- Idle waiting on Xfer (M2-M1)
- Overhead (M2-M1)
- Idle waiting on Xfer (M1-M0)
- Overhead (M1-M0)
- Leaf task execution (M0)

### Performance scaling

- SPE scaling on 2.4GHz Dual-Cell blade
- Scaling on P4 cluster with Infiniband interconnect

### Sequoia limitations

- Require explicit declaration of working sets
- Programmer must know what to transfer
- Some irregular applications present problems
- Task mapping somewhat laborious
- Autotuning helps
- Understand which parts can be automated better
Sequoia summary

- Enforce structuring already required for performance as integral part of programming model
- Make these hand optimizations portable and easier to perform

Sequoia summary (http://sequoia.stanford.edu)

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