EE382V: Principles in Computer Architecture
Parallelism and Locality
Fall 2008

Lecture 22 – Programming the Cell BE

Mattan Erez

UT ECE

The University of Texas at Austin

Outline

- Cell programming challenges review
- **Sequoia**
  - **Review + mapping**
- Other Cell programming tools
- Sequoia part courtesy Kayvon Fatahalian, Stanford
- All Cell related images and figures © Sony and IBM
- 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

- Key challenge in high performance programming is:
- **communication (not parallelism)**
  - **Latency**
  - **Bandwidth**

Streaming

- Streaming involves structuring algorithms as collections of independent [locality cognizant] computations with well-defined working sets.
- **This structuring may be done at any scale.**

Keep temporaries in registers
Cache/scratchpad blocking
Message passing on a cluster
Out-of-core algorithms

Streaming

•Streaming involves structuring algorithms as collections of independent [locality cognizant] computations with well-defined working sets.

Efficient programs exhibit this structure at many scales.

Roll of programming model

- **Encourage hardware-friendly structure**
- Bulk operations
- Bandwidth matters: structure code to maximize locality
- Parallelism matters: make parallelism explicit
- Awareness of memory hierarchy applies everywhere
  - Keep temporaries in registers
  - Cache/scratchpad blocking
  - Message passing on a cluster
  - Out-of-core algorithms

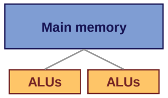
Sequoia's goals

- Facilitate development of hierarchy-aware stream programs …
- … that remain portable across machines
- Provide constructs that can be implemented efficiently without requiring advanced compiler technology (but facilitate optimization)
  - Place computation and data in machine
  - Explicit parallelism and communication
  - Large bulk transfers
- Get out of the way when needed

Hierarchical memory in Sequoia

Hierarchical memory

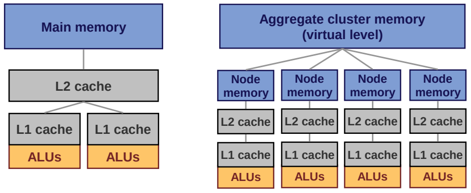
- Abstract machines as trees of memories

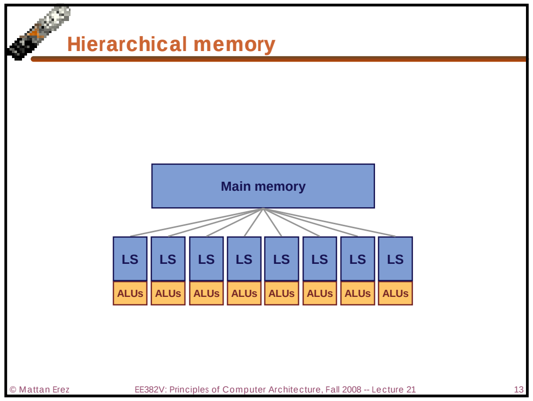


Similar to:
Parallel Memory Hierarchy Model
(Alpern et al.)

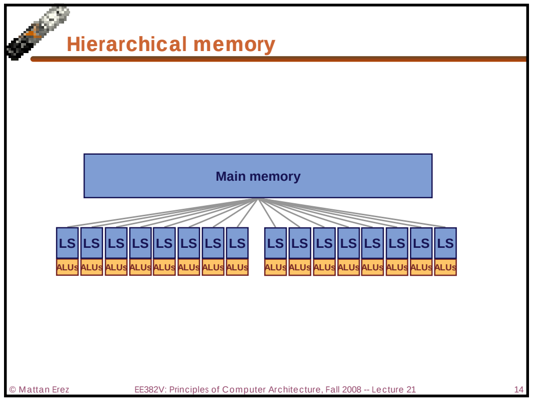
Hierarchical memory

- Abstract machines as trees of memories



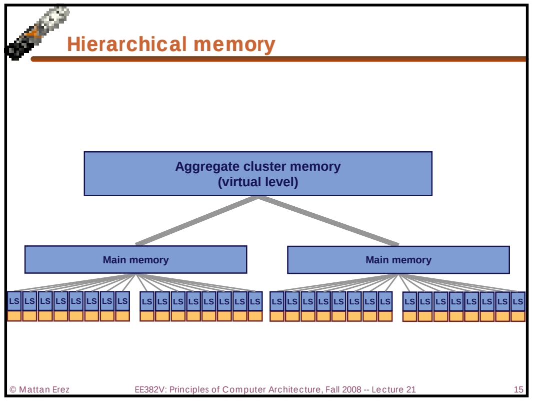


Hierarchical memory



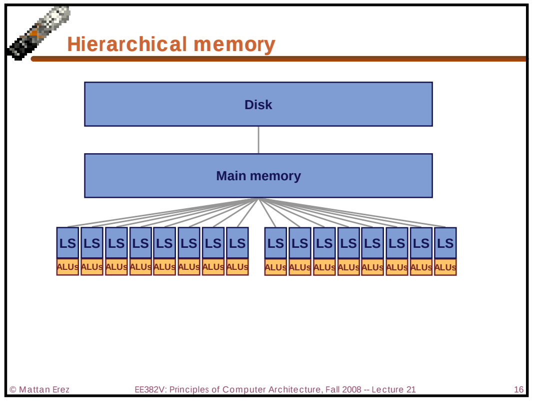
Hierarchical memory

Main memory
LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS
ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs



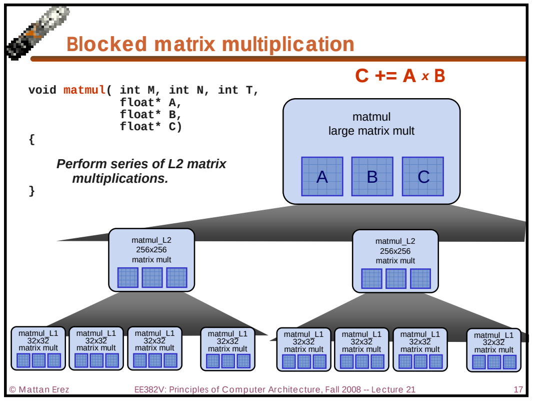
Hierarchical memory

Aggregate cluster memory
(virtual level)
Main memory
Main memory
LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS



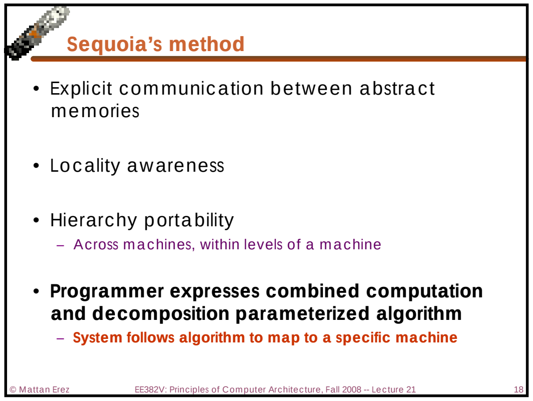
Hierarchical memory

Disk
Main memory
LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS LS
ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs ALUs



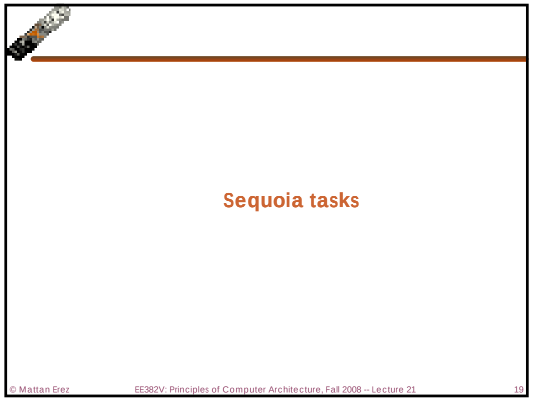
Blocked matrix multiplication

```
void matmul( int M, int N, int T,
             float* A,
             float* B,
             float* C)
{
    Perform series of L2 matrix
      multiplications.
}
```

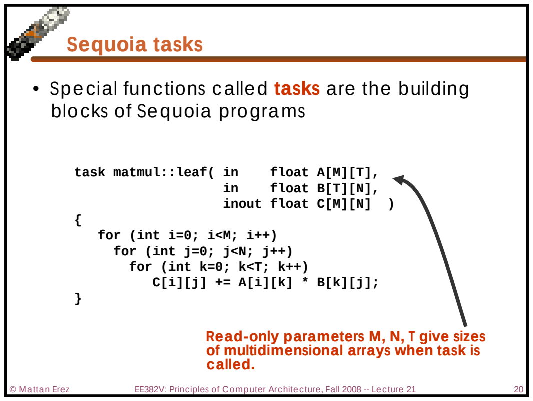


Sequoia's method

- 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 tasks

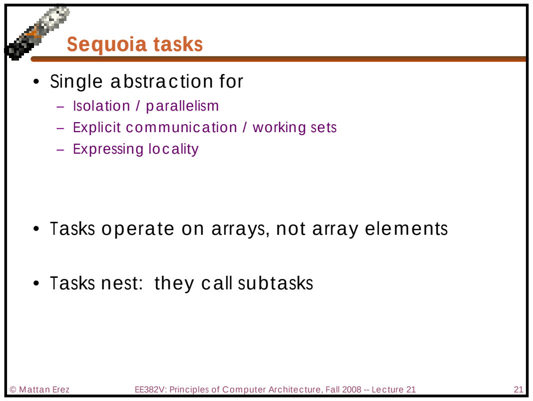


Sequoia tasks

- Special functions called **tasks** are the building blocks of Sequoia programs

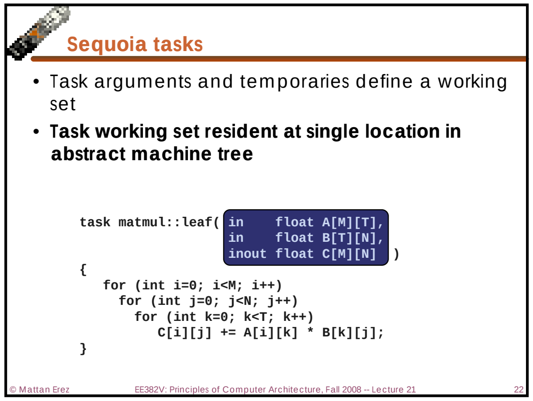
```
task matmul::leaf( in    float A[M][T],
                   in    float B[T][N],
                   inout float C[M][N]  )
{
   for (int i=0; i<M; i++)
     for (int j=0; j<N; j++)
       for (int k=0; k<T; k++)
          C[i][j] += A[i][k] * B[k][j];
}
```

Read-only parameters M, N, T give sizes of multidimensional arrays when task is called.



Sequoia tasks

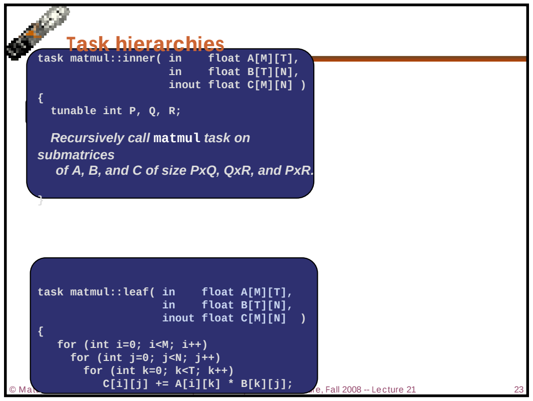
- Single abstraction for
  - Isolation / parallelism
  - Explicit communication / working sets
  - Expressing locality
- Tasks operate on arrays, not array elements
- Tasks nest: they call subtasks



Sequoia tasks

- Task arguments and temporaries define a working set
- **Task working set resident at single location in abstract machine tree**

```
task matmul::leaf( in    float A[M][T],
                   in    float B[T][N],
                   inout float C[M][N]  )
{
   for (int i=0; i<M; i++)
     for (int j=0; j<N; j++)
       for (int k=0; k<T; k++)
          C[i][j] += A[i][k] * B[k][j];
}
```



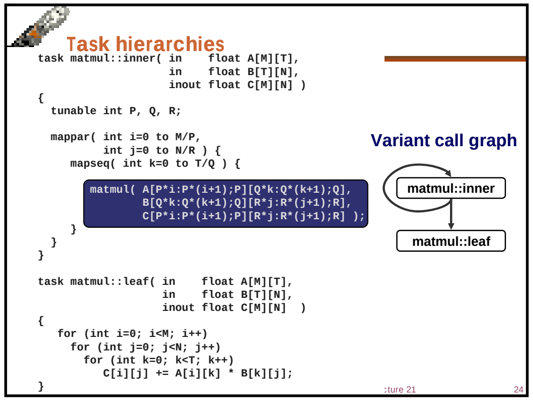
Task hierarchies

```
task matmul::inner( in    float A[M][T],
                    in    float B[T][N],
                    inout float C[M][N] )
{
  tunable int P, Q, R;
```

Recursively call `matmul` *task on submatrices of A, B, and C of size PxQ, QxR, and PxR.*

```
}
```

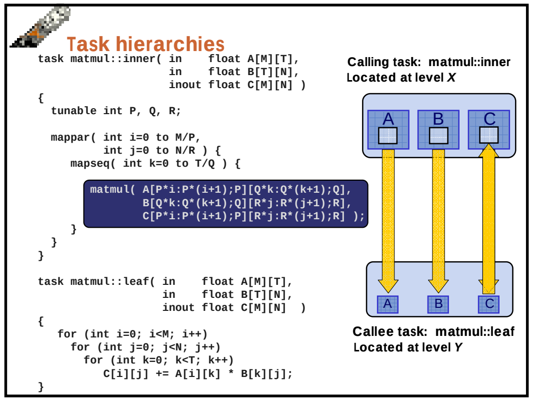
```
task matmul::leaf( in    float A[M][T],
                   in    float B[T][N],
                   inout float C[M][N]  )
{
   for (int i=0; i<M; i++)
     for (int j=0; j<N; j++)
       for (int k=0; k<T; k++)
          C[i][j] += A[i][k] * B[k][j];
```



Task hierarchies

```
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] );
     }
  }
}

task matmul::leaf( in    float A[M][T],
                   in    float B[T][N],
                   inout float C[M][N]  )
{
   for (int i=0; i<M; i++)
     for (int j=0; j<N; j++)
       for (int k=0; k<T; k++)
          C[i][j] += A[i][k] * B[k][j];
}
```

Variant call graph

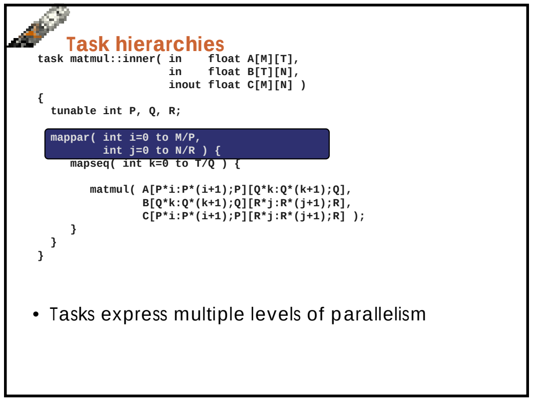


Task hierarchies

```
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] );
     }
  }
}

task matmul::leaf( in    float A[M][T],
                   in    float B[T][N],
                   inout float C[M][N]  )
{
   for (int i=0; i<M; i++)
     for (int j=0; j<N; j++)
       for (int k=0; k<T; k++)
          C[i][j] += A[i][k] * B[k][j];
}
```

Calling task: matmul::inner
Located at level *X*

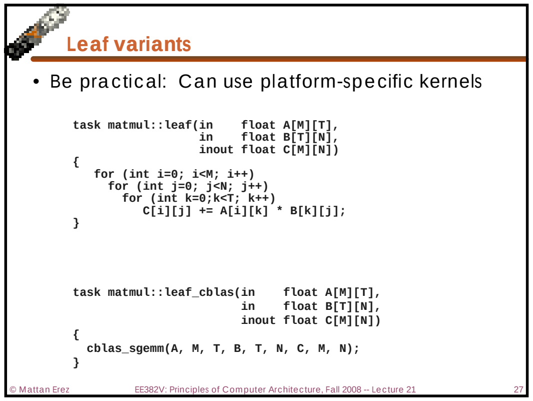
Callee task: matmul::leaf
Located at level *Y*



Task hierarchies

```
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] );
     }
  }
}
```

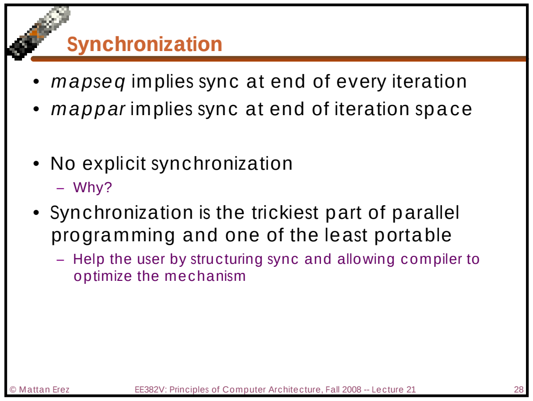
- Tasks express multiple levels of parallelism



Leaf variants

- Be practical: Can use platform-specific kernels

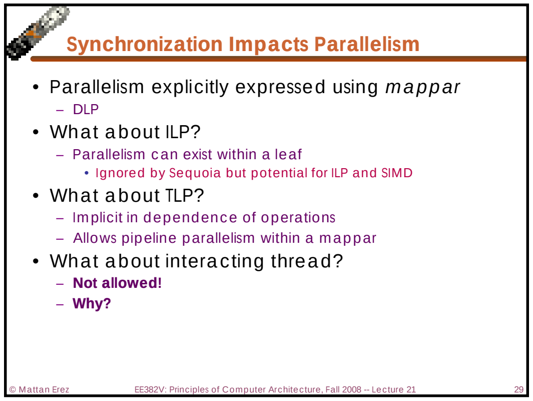
```
task matmul::leaf(in    float A[M][T],
                  in    float B[T][N],
                  inout float C[M][N])
{
   for (int i=0; i<M; i++)
     for (int j=0; j<N; j++)
       for (int k=0;k<T; k++)
          C[i][j] += A[i][k] * B[k][j];
}


task matmul::leaf_cblas(in    float A[M][T],
                        in    float B[T][N],
                        inout float C[M][N])
{
  cblas_sgemm(A, M, T, B, T, N, C, M, N);
}
```



Synchronization

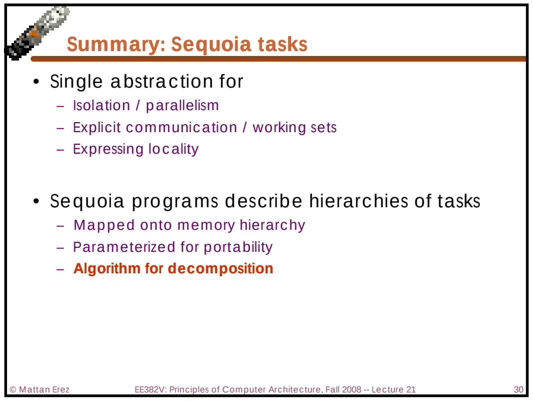
- *mapseq* implies sync at end of every iteration
- *mappar* implies sync at end of iteration space

- No explicit synchronization
  - Why?
- Synchronization is the trickiest part of parallel programming and one of the least portable
  - Help the user by structuring sync and allowing compiler to optimize the mechanism



Synchronization Impacts Parallelism

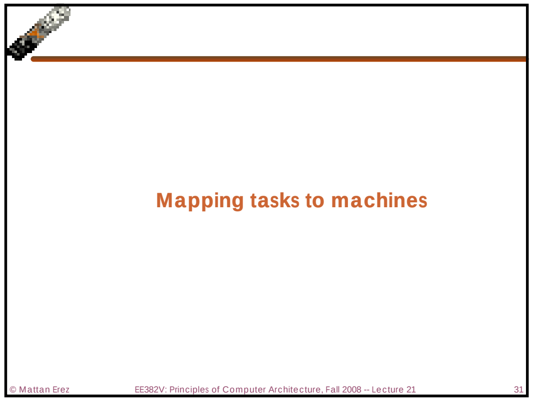
- Parallelism explicitly expressed using *mappar*
  - DLP
- What about ILP?
  - Parallelism can exist within a leaf
    - Ignored by Sequoia but potential for ILP and SIMD
- What about TLP?
  - Implicit in dependence of operations
  - Allows pipeline parallelism within a mappar
- What about interacting thread?
  - **Not allowed!**
  - **Why?**



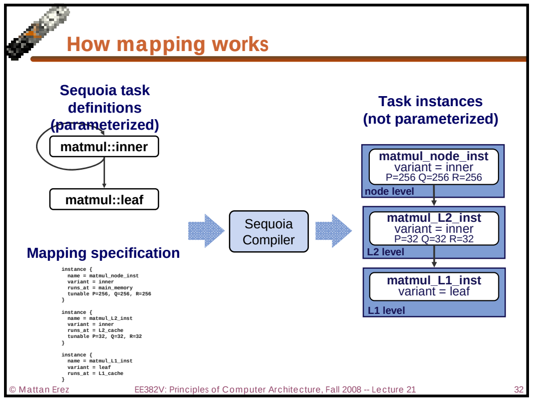
Summary: Sequoia tasks

- Single abstraction for
  - Isolation / parallelism
  - Explicit communication / working sets
  - Expressing locality

- Sequoia programs describe hierarchies of tasks
  - Mapped onto memory hierarchy
  - Parameterized for portability
  - **Algorithm for decomposition**



Mapping tasks to machines



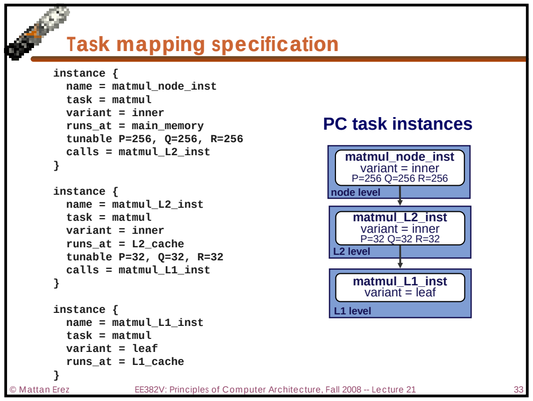
How mapping works

Sequoia task definitions (parameterized)

Mapping specification

```
instance {
  name = matmul_node_inst
  variant = inner
  runs_at = main_memory
  tunable P=256, Q=256, R=256
}

instance {
  name = matmul_L2_inst
  variant = inner
  runs_at = L2_cache
  tunable P=32, Q=32, R=32
}

instance {
  name = matmul_L1_inst
  variant = leaf
  runs_at = L1_cache
}
```

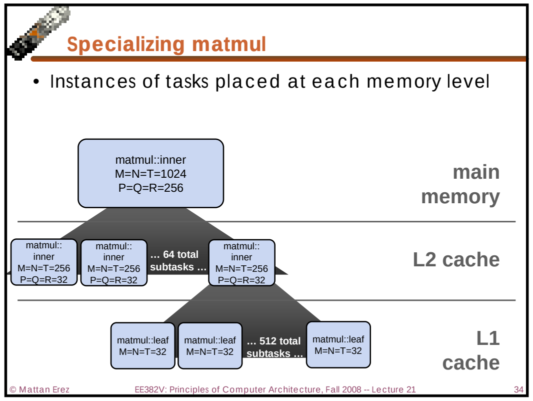
Task instances (not parameterized)



Task mapping specification

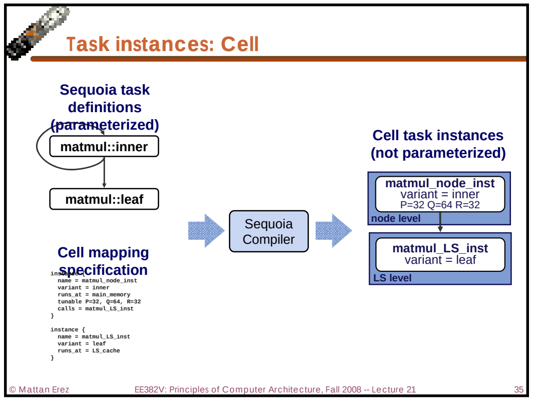
```
instance {
  name = matmul_node_inst
  task = matmul
  variant = inner
  runs_at = main_memory
  tunable P=256, Q=256, R=256
  calls = matmul_L2_inst
}

instance {
  name = matmul_L2_inst
  task = matmul
  variant = inner
  runs_at = L2_cache
  tunable P=32, Q=32, R=32
  calls = matmul_L1_inst
}

instance {
  name = matmul_L1_inst
  task = matmul
  variant = leaf
  runs_at = L1_cache
}
```

PC task instances



Specializing matmul

- Instances of tasks placed at each memory level



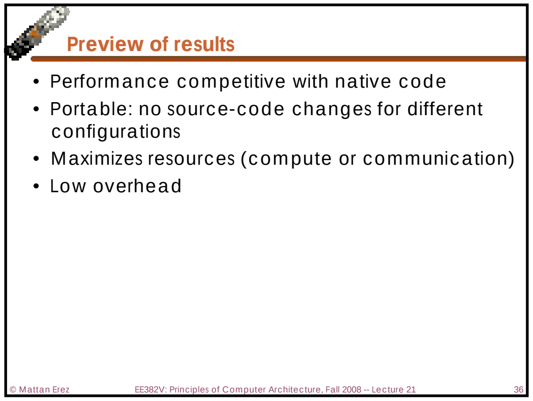
Task instances: Cell

Sequoia task definitions (parameterized)

Cell mapping specification

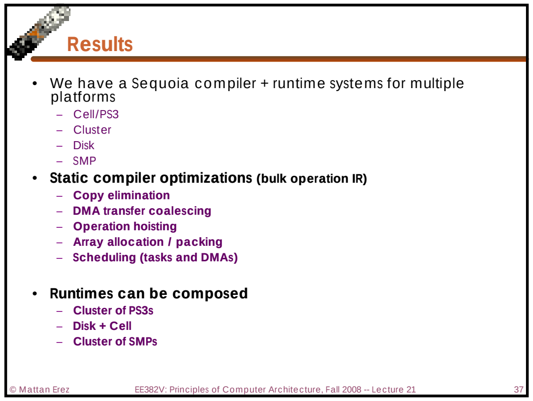
```
instance {
  name = matmul_node_inst
  variant = inner
  runs_at = main_memory
  tunable P=32, Q=64, R=32
  calls = matmul_LS_inst
}

instance {
  name = matmul_LS_inst
  variant = leaf
  runs_at = LS_cache
}
```

Cell task instances (not parameterized)



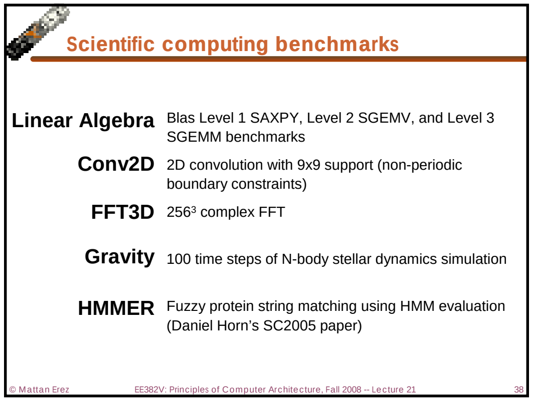
Preview of results

- Performance competitive with native code
- Portable: no source-code changes for different configurations
- Maximizes resources (compute or communication)
- Low overhead



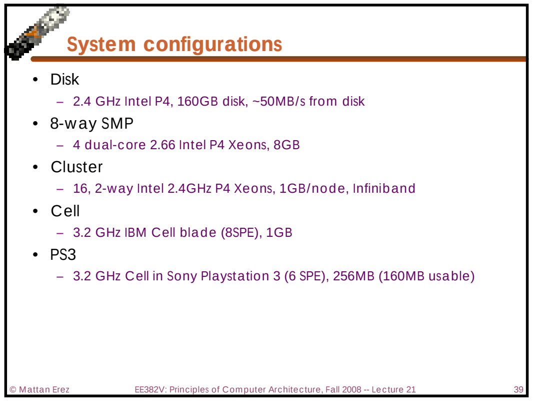
Results

- We have a Sequoia compiler + runtime systems for multiple platforms
  - Cell/PS3
  - Cluster
  - Disk
  - SMP
- **Static compiler optimizations (bulk operation IR)**
  - **Copy elimination**
  - **DMA transfer coalescing**
  - **Operation hoisting**
  - **Array allocation / packing**
  - **Scheduling (tasks and DMAs)**
- **Runtimes can be composed**
  - **Cluster of PS3s**
  - **Disk + Cell**
  - **Cluster of SMPs**



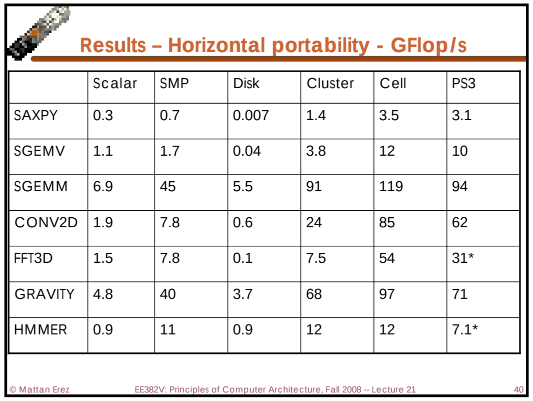
Scientific computing benchmarks

Linear Algebra	Blas Level 1 SAXPY, Level 2 SGEMV, and Level 3 SGEMM benchmarks
Conv2D	2D convolution with 9x9 support (non-periodic boundary constraints)
FFT3D	256^3 complex FFT
Gravity	100 time steps of N-body stellar dynamics simulation
HMMER	Fuzzy protein string matching using HMM evaluation (Daniel Horn's SC2005 paper)



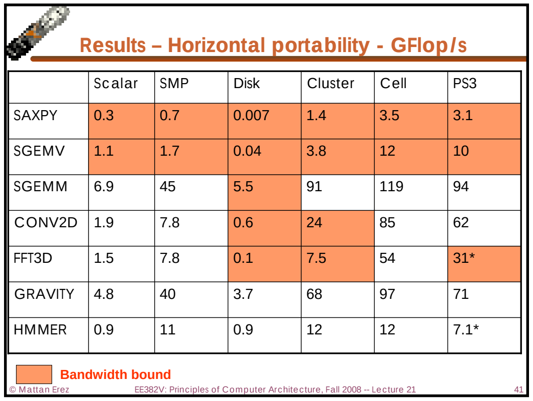
System configurations

- Disk
  - 2.4 GHz Intel P4, 160GB disk, ~50MB/s from disk
- 8-way SMP
  - 4 dual-core 2.66 Intel P4 Xeons, 8GB
- Cluster
  - 16, 2-way Intel 2.4GHz P4 Xeons, 1GB/node, Infiniband
- Cell
  - 3.2 GHz IBM Cell blade (8SPE), 1GB
- PS3
  - 3.2 GHz Cell in Sony Playstation 3 (6 SPE), 256MB (160MB usable)



Results – Horizontal portability - GFlop/s

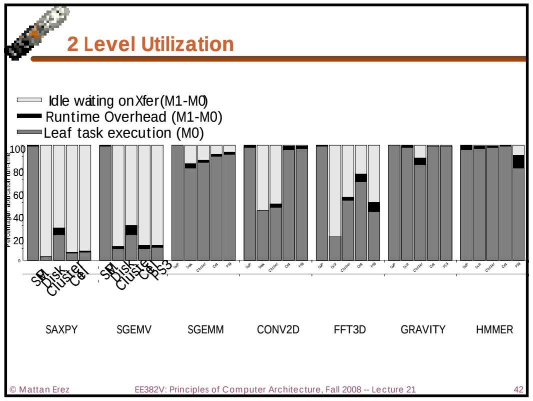
	Scalar	SMP	Disk	Cluster	Cell	PS3
SAXPY	0.3	0.7	0.007	1.4	3.5	3.1
SGEMV	1.1	1.7	0.04	3.8	12	10
SGEMM	6.9	45	5.5	91	119	94
CONV2D	1.9	7.8	0.6	24	85	62
FFT3D	1.5	7.8	0.1	7.5	54	31*
GRAVITY	4.8	40	3.7	68	97	71
HMMER	0.9	11	0.9	12	12	7.1*



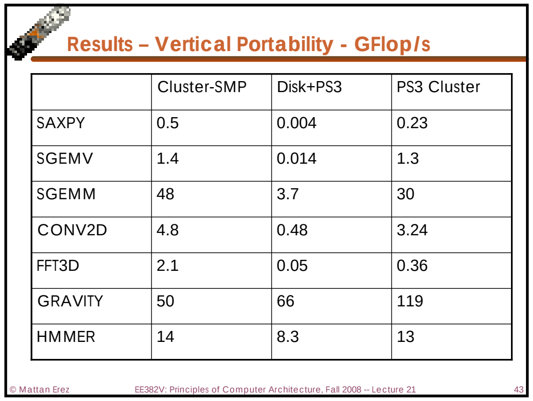
Results – Horizontal portability - GFlop/s

	Scalar	SMP	Disk	Cluster	Cell	PS3
SAXPY	🟧 0.3	🟧 0.7	🟧 0.007	🟧 1.4	🟧 3.5	🟧 3.1
SGEMV	🟧 1.1	🟧 1.7	🟧 0.04	🟧 3.8	🟧 12	🟧 10
SGEMM	6.9	45	🟧 5.5	91	119	94
CONV2D	1.9	7.8	🟧 0.6	🟧 24	85	62
FFT3D	1.5	7.8	🟧 0.1	🟧 7.5	54	🟧 31*
GRAVITY	4.8	40	3.7	68	97	71
HMMER	0.9	11	0.9	12	12	7.1*

🟧 **Bandwidth bound**

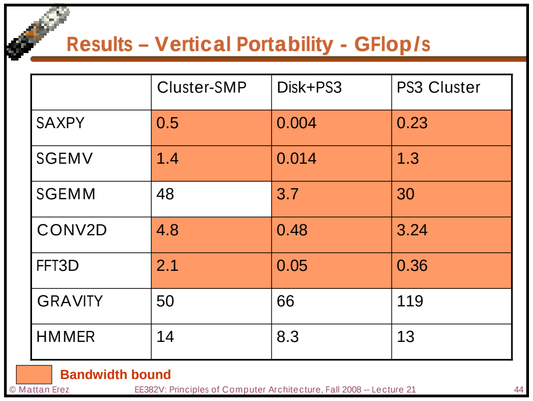


2 Level Utilization



Results – Vertical Portability - GFlop/s

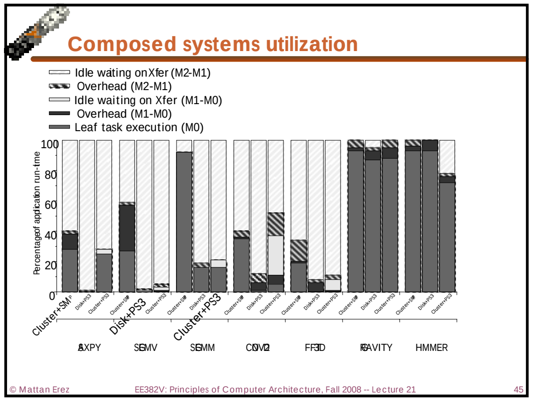
	Cluster-SMP	Disk+PS3	PS3 Cluster
SAXPY	0.5	0.004	0.23
SGEMV	1.4	0.014	1.3
SGEMM	48	3.7	30
CONV2D	4.8	0.48	3.24
FFT3D	2.1	0.05	0.36
GRAVITY	50	66	119
HMMER	14	8.3	13



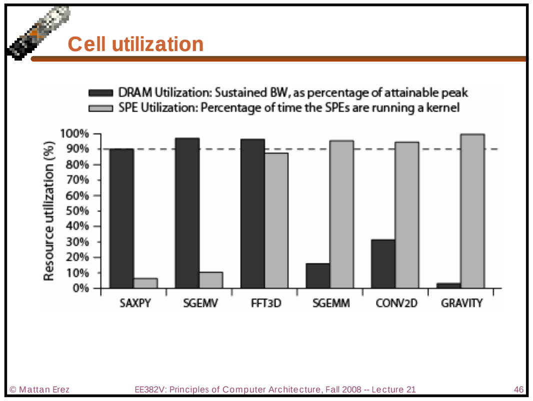
Results – Vertical Portability - GFlop/s

	Cluster-SMP	Disk+PS3	PS3 Cluster
SAXPY	0.5	0.004	0.23
SGEMV	1.4	0.014	1.3
SGEMM	48	3.7	30
CONV2D	4.8	0.48	3.24
FFT3D	2.1	0.05	0.36
GRAVITY	50	66	119
HMMER	14	8.3	13

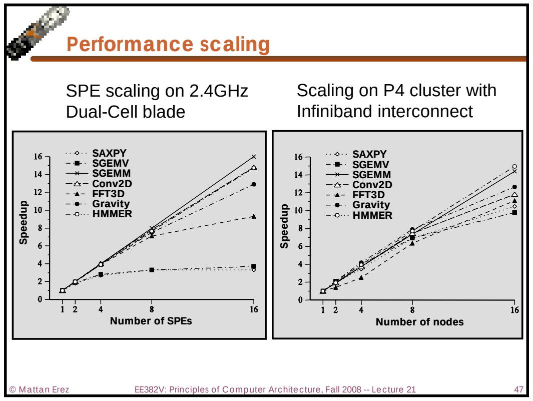
🟧 Bandwidth bound



Composed systems utilization



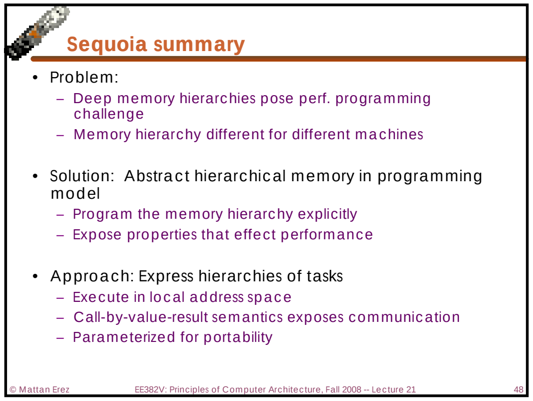
Cell utilization



Performance scaling

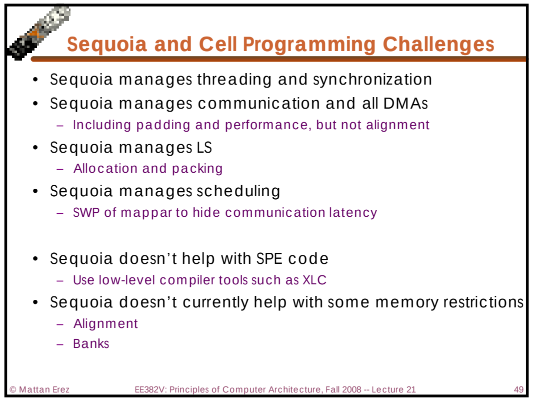
SPE scaling on 2.4GHz Dual-Cell blade

Scaling on P4 cluster with Infiniband interconnect



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 effect 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
  - Banks

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