CPEG 852 — Advanced Topics in Computing Systems
The EARTH Program Execution Model
Hybrid von Neumann/Dataflow Models

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October 20-27, 2015

Outline

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EARTH: The Secret Origins

- At the beginning of the 1990's, dataflow machines are considered obsolete compared to their vector and superscalar cousins
- Some people still think dataflow as a founding principle for models of computation is still sound
- Idea: mix RISC-like processors for the low-level execution and dataflow semantics for high-level concepts
  - Technically, this is more or less the definition of *macro-dataflow*
- EARTH is a bit different from macro-dataflow – see next slide

A Short Detour: Macro-Dataflow I

Macro-Dataflow: a Description

- Concept: take a sequence of instructions, and group them into a macro-dataflow actor
- A macro-dataflow actor has input arcs (for the "tokens") and output arcs
- A macro-dataflow actor has no state except the one formed by its input tokens
- Firing rule: when all input arcs have a token present, the macro-dataflow actor may fire
- A macro-dataflow actor always places tokens on its ouputs arcs *all at once*

Why EARTH Does Not Quite Follow a Macro-Dataflow Model

- In EARTH, actors *do* execute an uninterruptible sequence of instructions (like in macro-dataflow)
- But an EARTH actor can signal/produce data at any time during its execution
  - It is more "loose" in its asynchrony

What Is a Thread in EARTH?

- Parallel function invocation (threaded function invocation)
- A code sequence defined (by the user or a compiler) to be a thread (fiber)
- Usually, a threaded function's body will be partitioned into multiple threads/fibers

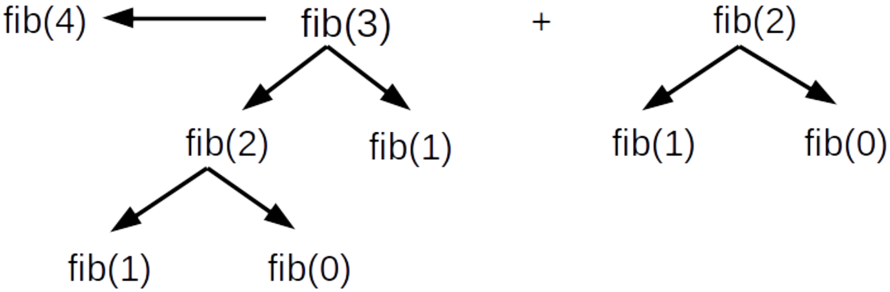
Outline

A Simple Example: Naïve Fibonacci

```c
u64  fib(u64 n) {
    if (n < 2) return n;
    return fib(n-1) + fib(n-2);
}
```

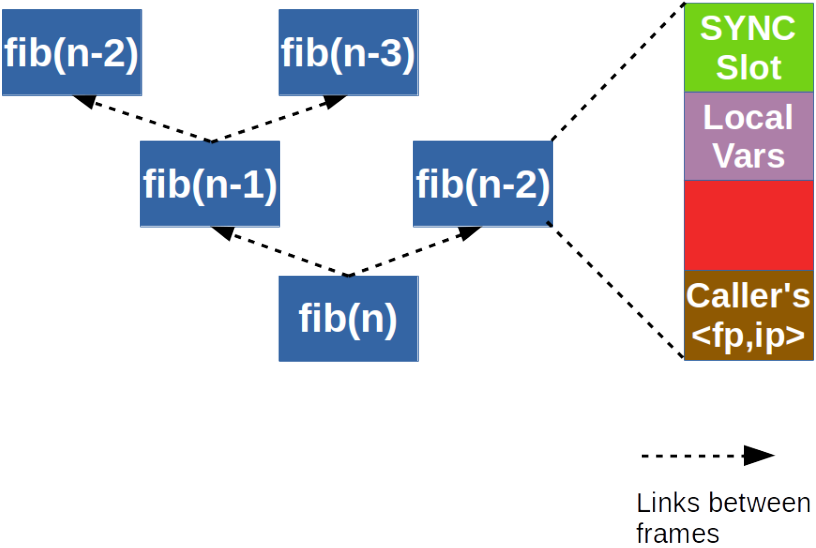
A Simple Example: Naïve Fibonacci

Computation Tree Example



A Simple Example: Naïve Fibonacci

Activation Frame Tree



Known Short Latencies, Known Long Latencies, and Unknown Latencies

An Example

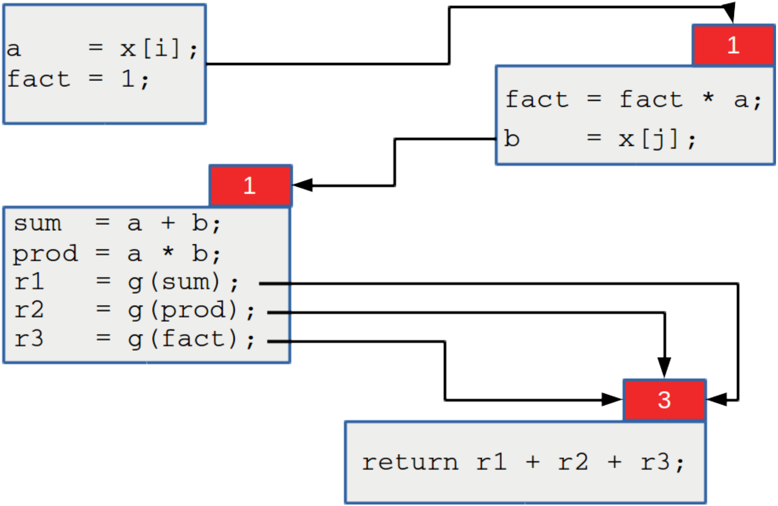
```
int  f(int *x, int i, int j) {
    int a, b, sum, prod, fact;
    int r1, r2, r3;
    a    = x[i];
    fact = 1;
    fact = fact * a;
```

```
    b    = x[j];
    sum  = a + b;
    prod = a * b;
    r1   = g(sum);
    r2   = g(prod);
    r3   = g(fact);

    return r1 + r2 + r3;
}
```

Known Short Latencies, Known Long Latencies, and Unknown Latencies

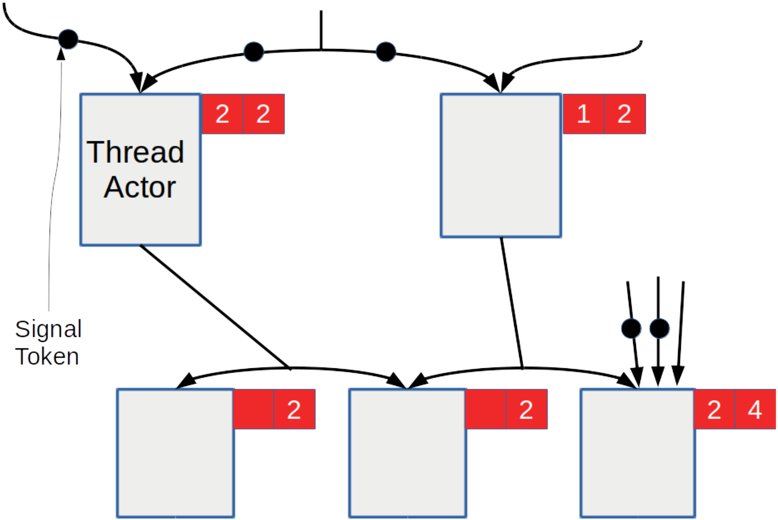
Partitioning Into Fibers



Fibers

- A fiber shares its enclosing "frame" with other fibers within the same threaded function invocation
- The state of a fiber includes:
  - Its instruction pointer
  - Its "temporary register set"
- A fiber is "ultra-lightweight:" it does not need dynamic storage (frame) allocation.
- Our focus: non-preemptive threads – which we call fibers

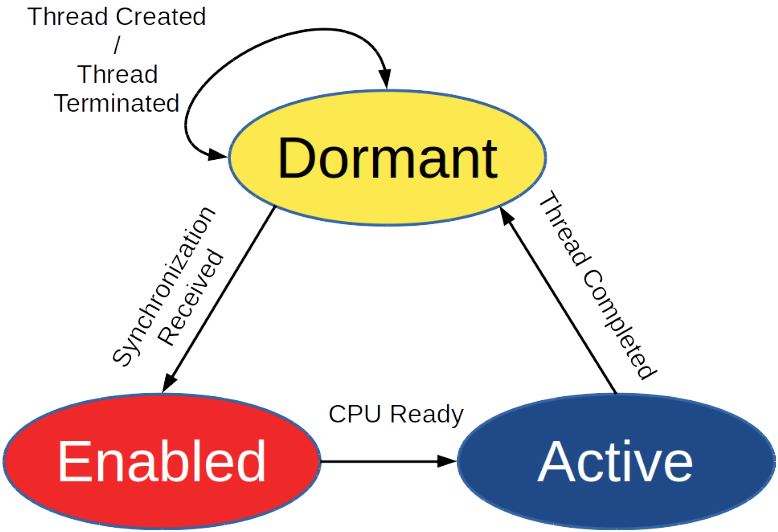
The EARTH Execution Model



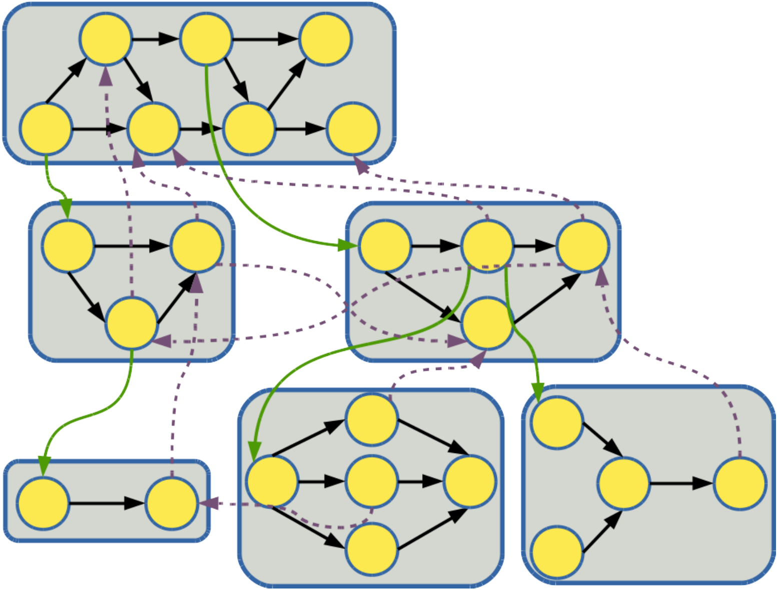
Fibers Firing Rule

- A fiber becomes enabled if it has received all input signals
- An enabled fiber may be selected for execution when the required hardware resource has been allocated
- When a fiber finishes its execution, a signal is sent to all destination threads to update the corresponding synchronization slots

Fibers States

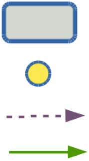


The EARTH Model of Computation



The EARTH Multithreaded Execution Model

Two levels of multithreading:
- Threaded procedures
- Fibers

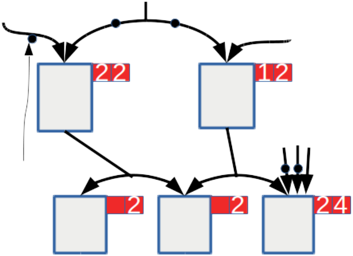


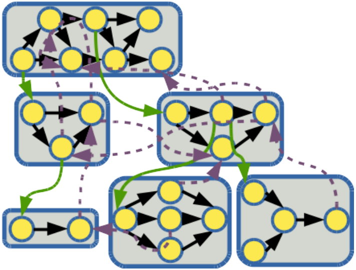
Async. function invocation

Fiber within frame

SYNC op.

Invoke threaded function





EARTH vs. Cilk

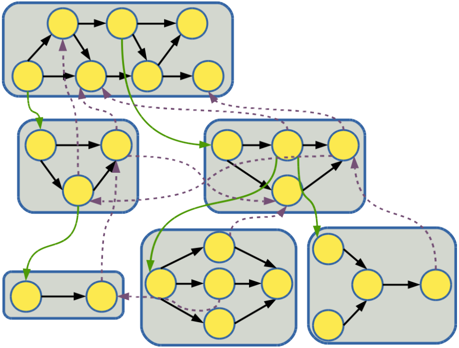


Figure: EARTH Model

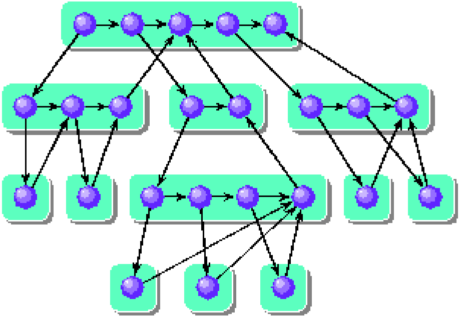
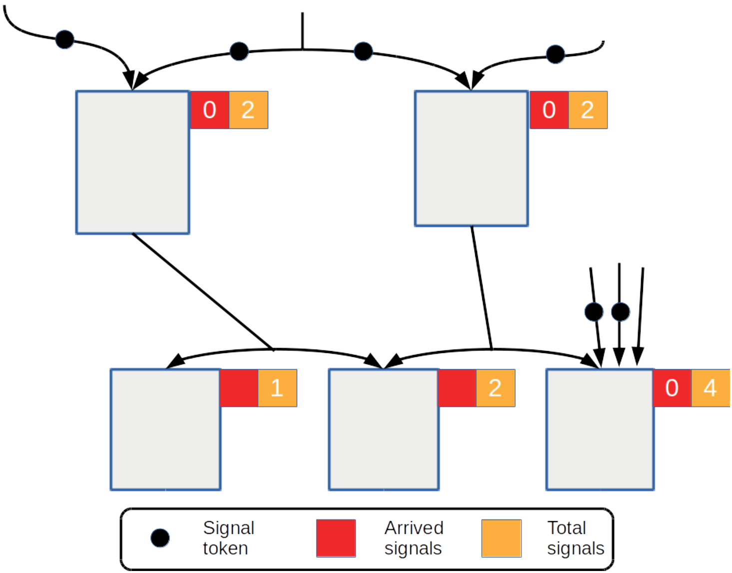


Figure: Cilk Model

The Fiber Execution Model



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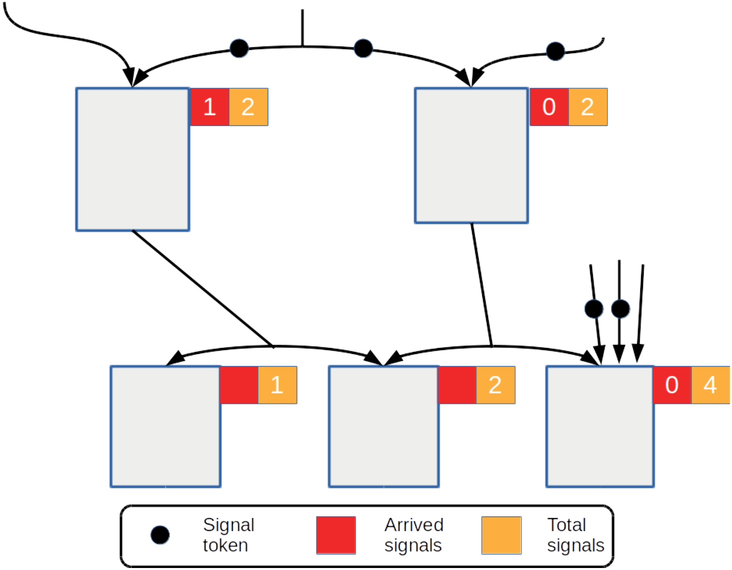

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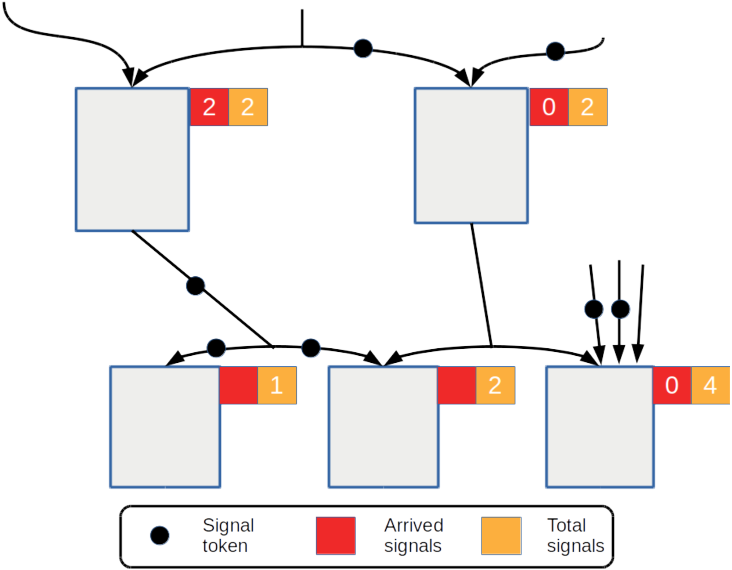

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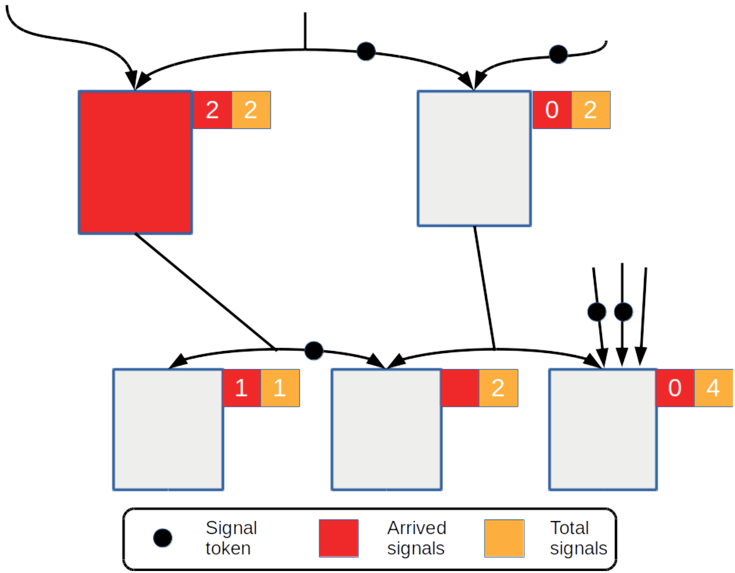

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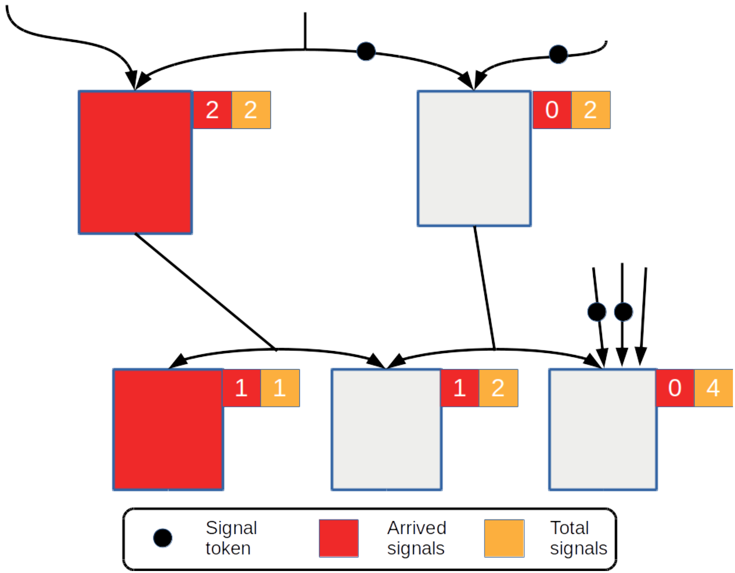

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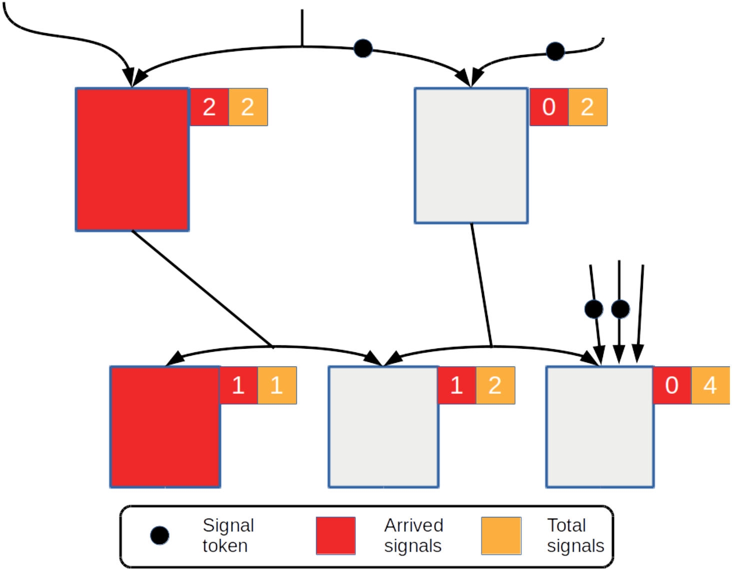

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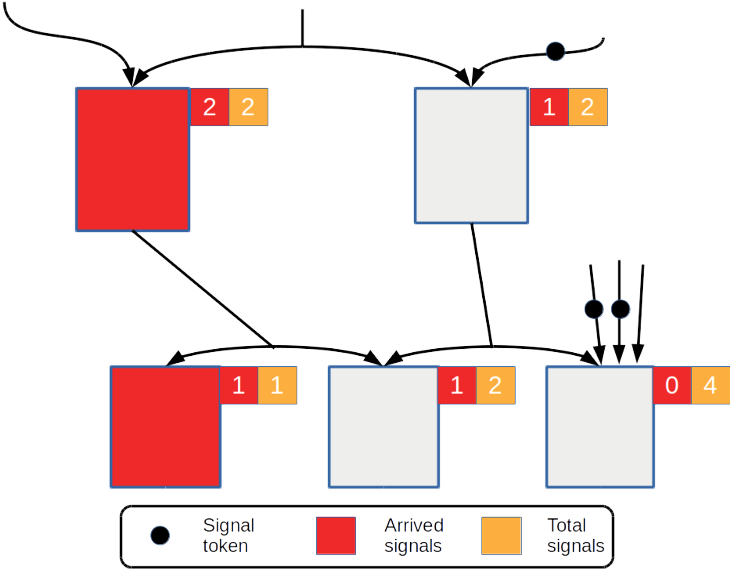

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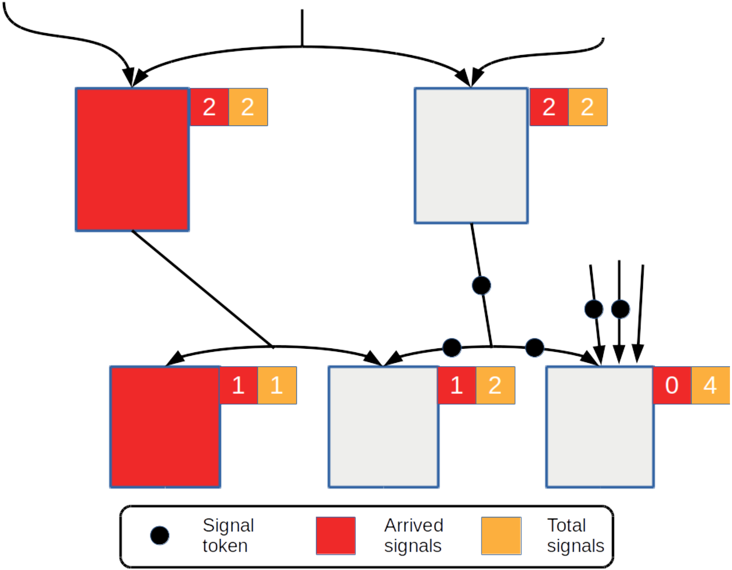

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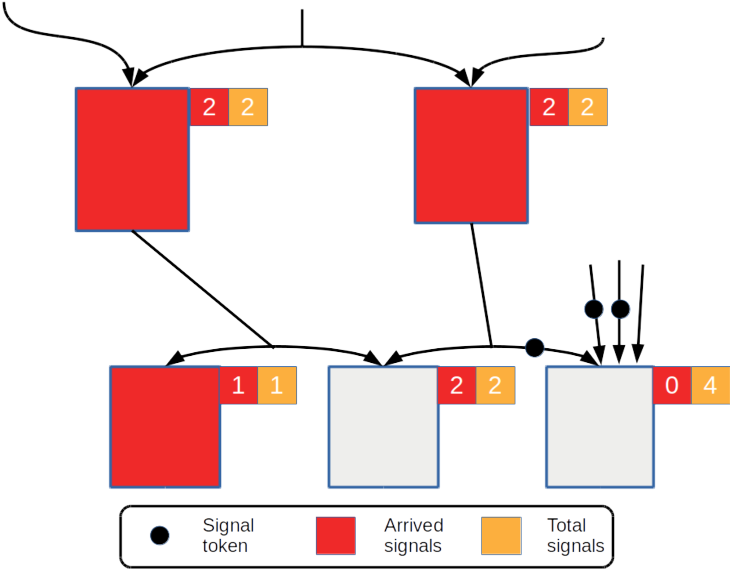

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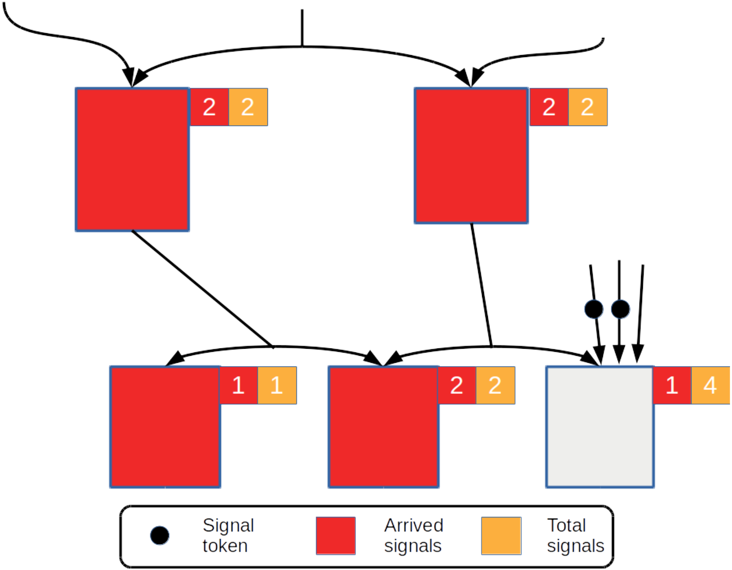

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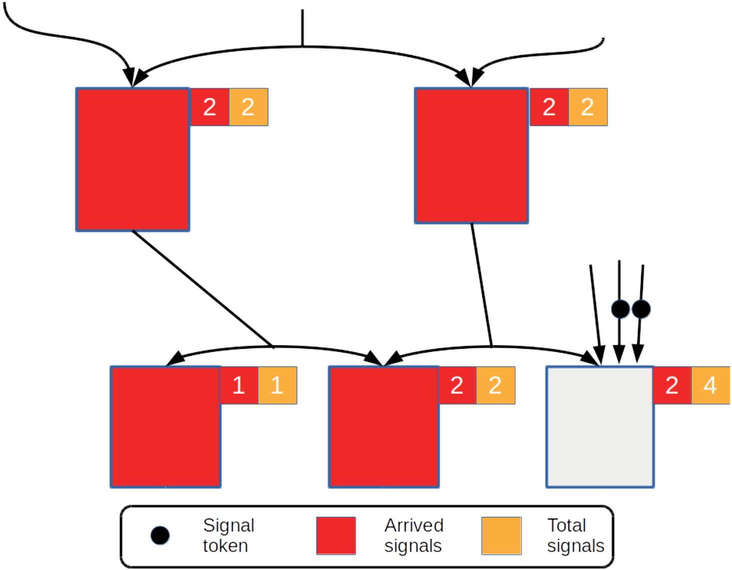

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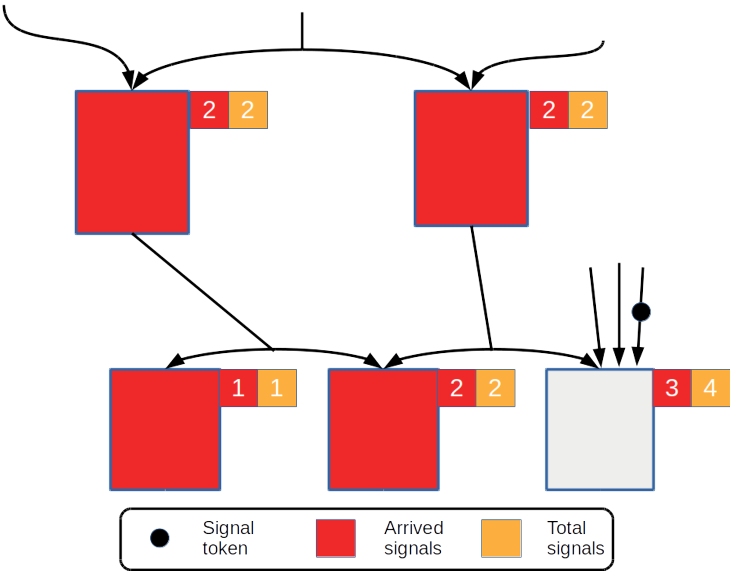

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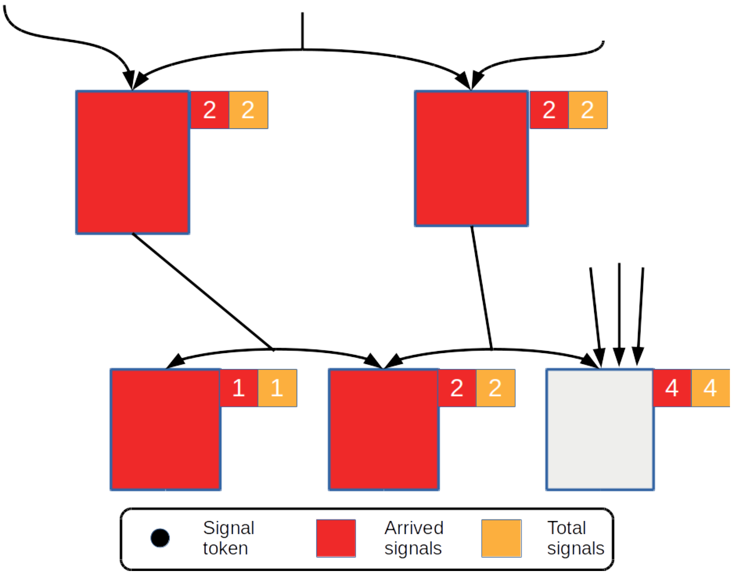

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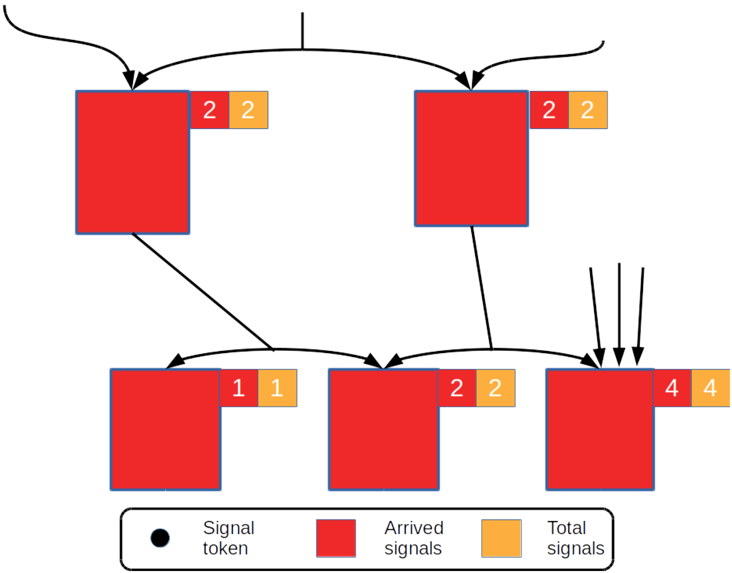
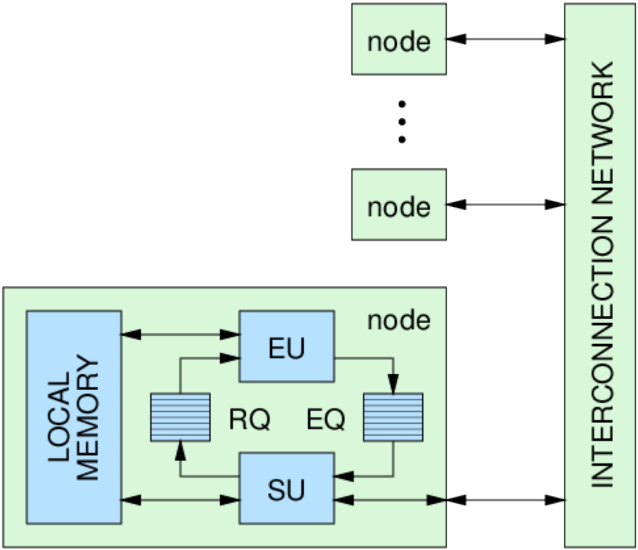
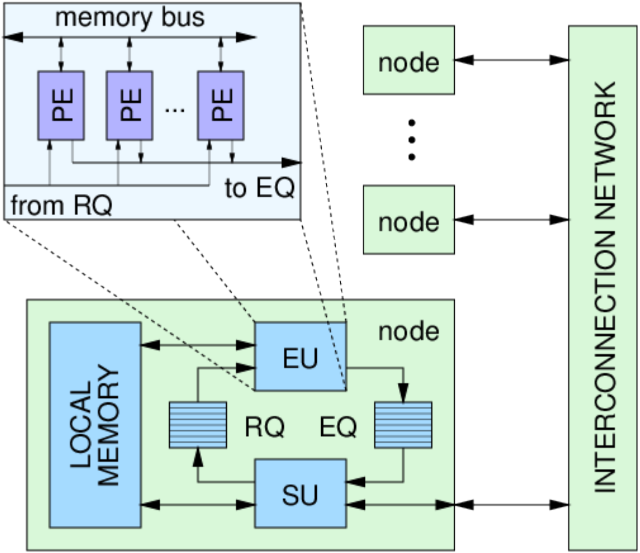


Outline

The EARTH Abstract Machine



The EARTH Abstract Machine



EARTH's Evaluation Platforms

EARTH-Manna

Implement EARTH on a bare metal tightly coupled multi-processor

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Implement EARTH on a bare metal tightly coupled multi-processor

EARTH-IBM-SP

Plan to implement EARTH on an off-the-shelf commercial parallel machine (IBM SP2/SP3)

EARTH's Evaluation Platforms

EARTH-Manna

Implement EARTH on a bare metal tightly coupled multi-processor

EARTH-IBM-SP

Plan to implement EARTH on an off-the-shelf commercial parallel machine (IBM SP2/SP3)

EARTH on Clusters

- EARTH on Beowulf
- Implement EARTH on a cluster of UltraSPARC SMP workstations connected by Fast Ethernet

EARTH's Evaluation Platforms

EARTH-Manna

Implement EARTH on a bare metal tightly coupled multi-processor

EARTH on Clusters

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EARTH-IBM-SP

Plan to implement EARTH on an off-the-shelf commercial parallel machine (IBM SP2/SP3)

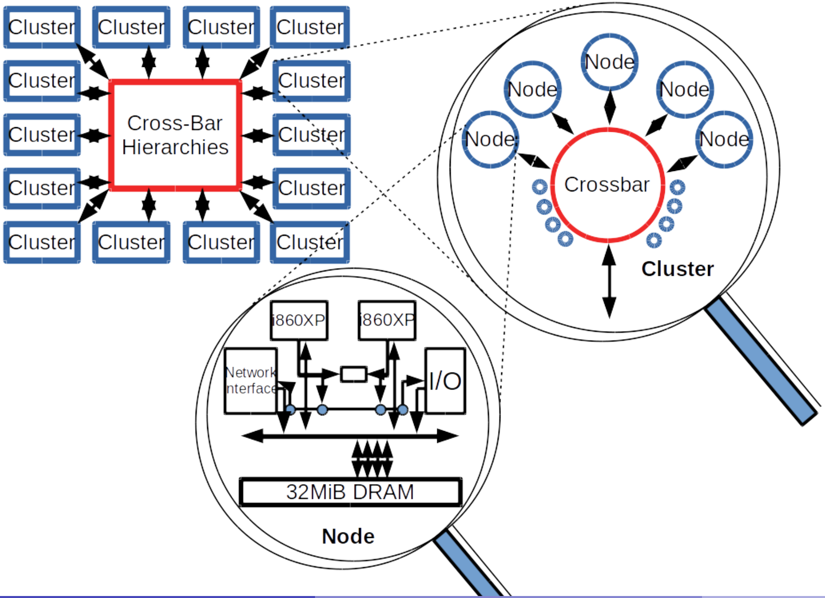
Note—Benchmark codes were all written using EARTH Threaded-C: The API for EARTH Execution and Abstract Machine Models

Outline

Open Issues

- Can a multithreaded program execution model support high scalability for large-scale parallel computing while maintaining high processing efficiency?
- If so, can this be achieved without exotic hardware support?
- Can these open issues be addressed both qualitatively and quantitatively with performance studies of real-life benchmarks?

The EARTH-MANNA Multiprocessor Testbed



Main Features of EARTH Multiprocessor

- Fast thread context switching
- Efficient parallel function invocation
- Good support of fine-grain dynamic load-balancing
- Efficient support of split-phase transactions
- Brings together the concept of fibers and dataflow

Main Features of EARTH Multiprocessor

- Fast thread context switching
- Efficient parallel function invocation
- Good support of fine-grain dynamic load-balancing
- Efficient support of split-phase transactions
- Brings together the concept of fibers and dataflow
- All that using off-the-shelf microprocessors!

EARTH-C Compiler Environment

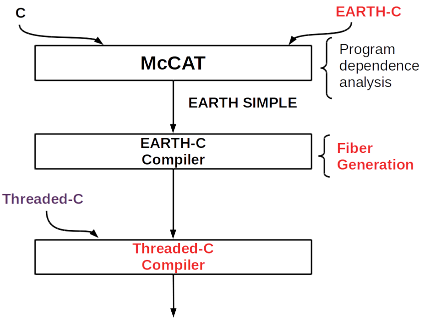


Figure: EARTH Compilation Environment

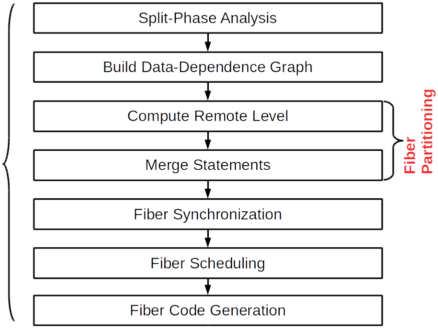


Figure: EARTH-C Compiler

- Overview
- Microbenchmarking:
  - Stress-testing
  - Measure performance of basic EARTH mechanisms for communication and synchronization
- Kernel benchmarking:
  - Speedup
  - USE value (Uni-node Support Efficiency)
    - *i.e.*, compare pure sequential kernel vs. single-node EARTH kernel
  - Latency tolerance capacity

Note—It is important to define your own performance "features" and/or "parameters" that best distinguishes your model from your competitors

EARTH Benchmark Suite (EBS)

Benchmark Name	Problem Size	Problem Domain	Characteristics
Ray Tracing	512×512	Image Processing	Class A
Wave-2D	150×150	Fluid Dynamics	Class A
Tomcatv	257	Scientific computation	Class A
2D-SLT	80×80	Fluid Dynamics	Class A
Matrix Multiply	480×480	Numerical computation	Class A
Barnes-Hut	8192 bodies	N-Body simulation	Class B
MP3D	18 K particles	Fluid Flow simulation	Class B
EM3D	20 K nodes	Electromagnetic wave simulation	Class B
Sampling Sorting	64 K	Sorting problem	Class B
Gauss Elimination	720×720	Numerical computation	Class B
Protein Folding	$3 \times 3 \times 3$ cube	Chemistry	Class B
Eigenvalue	2999	Numerical computation	Class B
Vertex Enumeration	10	Pivot-based searching	Class B
TSP	10	Graph searching	Class B
Paraffins	20	Chemistry	Class B
N-Queen	12	Graph searching	Class B
Power	10000	Power system optimization	Class B
Voronoi	64 K	Graph Partitioning	Class B
Heuristic-TSP	32 K	Searching problem	Class B
Tree-Add	1 M	Graph Searching	Class B

Highlighted benchmarks are implemented using a portable version of Threaded-C

- Efficient multithreading support is possible with off-the-shelf processor nodes with low overhead
  - At the time: context-switch time ≈ 35 cycles
  - Nowadays, this figure would most likely be bigger by at least one order of magnitude, probably ≈ 20 times bigger
    - This is speculation, but even with a bare-metal implementation, there is a ≈ 3× difference between memory bus and processor frequencies.
- A multithreaded program execution model an make a big difference
  - Results from the EARTH Benchmark Suite (EBS)

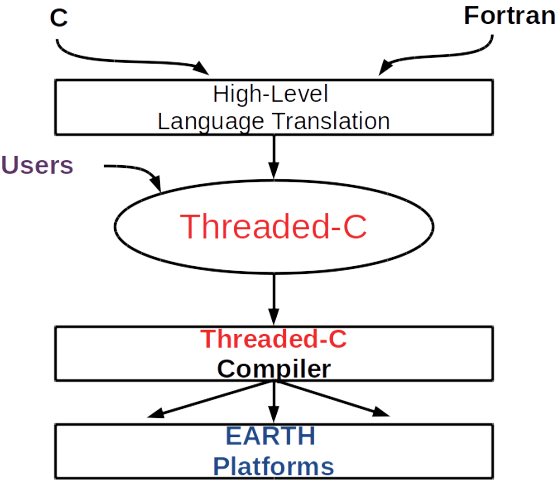
Outline

Outline

Threaded-C: A Base Language

- Serves as a target language for high-level language compilers
- Serves as a machine language for the EARTH architecture

The Role of Threaded-C



Outline

Features of Threaded Programs

- Thread partition
  - Thread length vs. useful parallelism
  - Where to “cut” a dependence and create a “split-phase?”
- Split-phase synchronization and communication
- Parallel threaded function invocation
- Dynamic load-balancing
- Other advanced features: fibers and dataflow

Base operations

- Thread synchronization and scheduling ops
  - SPAWN
  - SYNC
- Split-phase data & synchronization operations
  - GET_SYNC
  - DATA_SYNC
- Threaded function invocation and load-balancing operations
  - INVOKE
  - TOKEN

The EARTH Instruction Set I

- Basic insructions:
  - Arithmetic, logic, branching
  - Typical RISC instructions, *e.g.*, those from the i860
- Thread Switching
  - `FETCH_NEXT`
- Synchronization
  - `SPAWN fp, ip`
  - `SYNC fp, ss_off`
  - `INIT_SYNC ss_off, sync_cnt, reset_cnt, ip`
  - `INCR_SYNC fp, ss_off, value`
- Data transfers & synchronization
  - `DATA_SPAWN value, dest_addr, fp, ip`
  - `DATA_SYNC value, dest_addr, fp, ss_off`
  - `BLOCKDATA_SPAWN src_addr, dst_addr, size, fp, ip`
  - `BLOCKDATA_SYNC src_addr, dst_addr, size, fp, ss_off`

The EARTH Instruction Set II

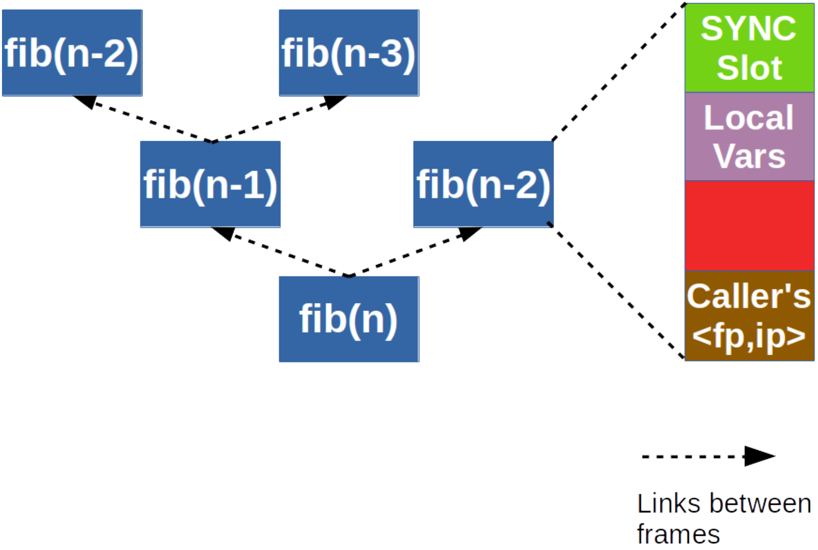
- Split-phase data requests
  - GET_SPAWN src_addr, dst_addr, fp, ip
  - GET_SYNC src_addr, dst_addr, fp, ss_off
  - GET_BLOCK_SPAWN src_addr, dst_addr, fp, ip
  - GET_BLOCK_SYNC src_addr, dst_addr, fp, ss_off
- Function invocation
  - INVOKE dst_PE, func_name, num_params, params
  - TOKEN func_name, num_params, params
  - END_FUNCTION

Outline

- **Ray Tracing** is a program for rendering 3-D photo-realistic images
- **Protein Folding** is an application that computes all possible foldings tructures of a given polymer
- **TSP** is an application to find a minimal-length Hamiltonian cycle in a graph with N cities and weighted paths.
- **Tomcatv** is one of the SPEC benchmarks which operates upon a mesh
- **Parrafins** is another application which enumerates distinct isomers paraffins
- **2D-SLT** is a program implementing the 2D-SLT Semi-Lagrangian Advection Model on a Gaussian Grid for numerical weather predication
- **N-Queens** is a benchmark program typical of graph searching problem.

Outline

Reminder: Tree of Activation Frames



The Fibonacci Example

Definition: Fibonacci Sequence

$$\begin{cases} U_0 = 0 \\ U_1 = 1 \\ U_n = U_{n-1} + U_{n-2} \end{cases}, \forall n \in \mathbb{N}$$

```
u64  fib(u64 n) {
    if (n < 2) return n;
    return fib(n-1) + fib(n-2);
}
```

The Fibonacci Example
Threaded-C Version

```
THREADED fib(u64 n, u64* result, sslot_t done) {
THREAD-0:
    u64 sum1 = 0, sum2 = 1;
    sslot_t slot1 = ... , /*,  , (0,0),  , */,
            slot2 = ... , /*,  , (2,2),  , */;
    if (n < 2) {
        DATA_RSYNC(n, result, done);
    } else {
        TOKEN (fib, n-1, &sum1, slot1);
        TOKEN (fib, n-2, &sum2, slot2);
    }
    END_THREAD();
THREAD-1:
    DATA_RSYNC(sum1+sum2;, result, done);
    END_THREAD();

    END_FUNCTION;
}
```

Although the definition is general, we set our numbers in either $\mathbb{R}$ or $\mathbb{C}$.
We generalize with the set $\mathbb{K}$.
Let A, B, and C be matrices, with $A_{M,K}$, $B_{K,N}$, $C_{M,N} \in \mathbb{K} \times \mathbb{K}$; let α, $\beta \in \mathbb{K}$. Then,

$$C_{M,N} \leftarrow \beta \times C_{M,N} + \alpha \times A_{M,K} \times B_{K,N}$$

One element $c_{i,j}$ of $C_{M,N}$ is computed as such:

$$c_{i,j} = \beta \cdot c_{i,j} + \alpha \cdot \sum_{k=1}^{k=K} a_{i,k} \cdot b_{k,j},\ a_{i,k} \in A_{M,K},\ b_{k,j} \in B_{K,N}$$

GEneral Matrix Multiplication (GEMM)

Square Case — Naïve Sequential Code

Note—To simplify the problem, we assume $\beta = 0$, $\alpha = 1,0$. In other words, we compute $C_{N,N} = A_{N,N} \times B_{N,N}$.

```
void dgemm(const double  beta,          double* C,
           const double  alpha,
           const double* A,     const double* B,
           const size_t N)
{
    for (size_t i = 0; i < N; ++i) {
        for (size_t j = 0; j < N; ++j) {
            c[i*N+j] = beta * c[i*N+j];
            for (size_t k = 0; k < N; ++k)
              c[i*N+j] += alpha * A[i*N+k] * b[k*N+j];
        }
    }
}
```

The Fibonacci Example

Threaded-C Version — Outer Product

Note—We assume the B matrix is correctly transposed to allow row-major traversal.

```
THREADED void dgemm(double* C, const double* A, const double* B,
                    const size_t N)
{
    double *row_a, *column_b;
    sslot_t slot0 = init_sslot(0,0),
            slot1 = init_sslot(N*N,N*N);
THREAD-0:
    for (size_t i = 0; i < M; ++i) {
        for (size_t j = 0; j < N; ++j) {
            row_a    = a[i];
            column_b = b[j];
            for (size_t k = 0; k < K; ++k)
                TOKEN (inner, &c[i*N+j], row_a, column_b, slot2);
        }
    }
    END_THREAD();
THREAD-1:
    RETURN(); , //,  , do,  , nothing
    END_THREAD();

    END_FUNCTION;
}
```

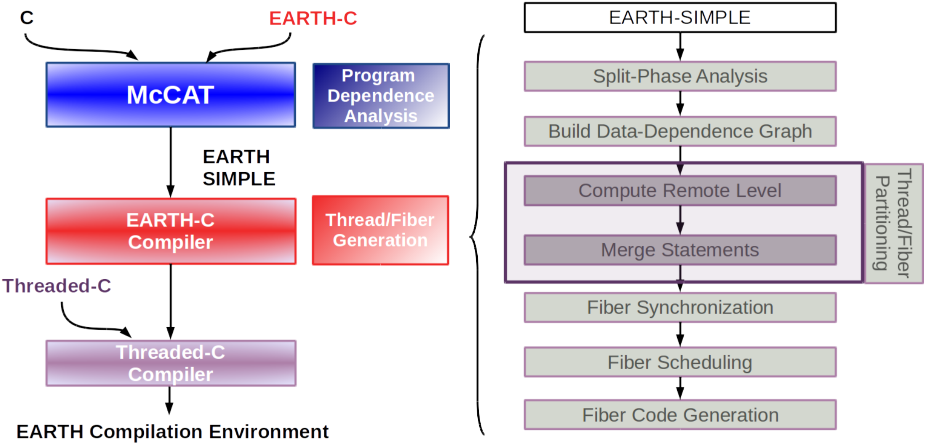
The Fibonacci Example

Threaded-C Version — Inner Product

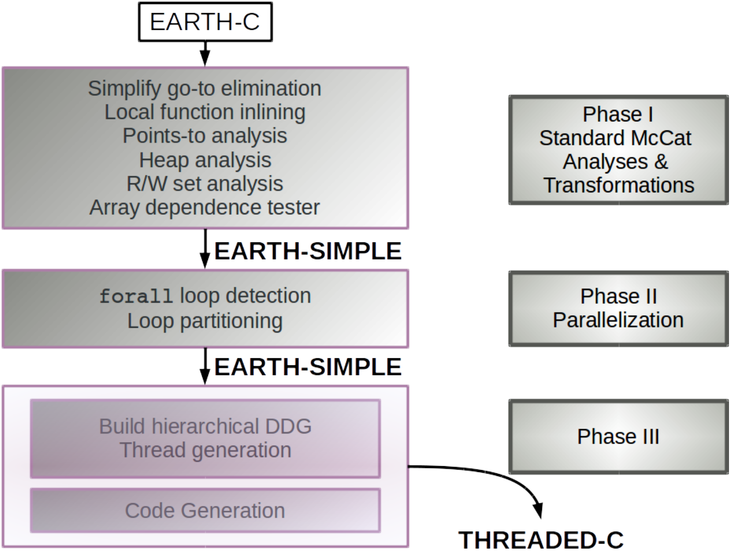
Note—We assume the B matrix is correctly transposed to allow row-major traversal.

```
THREADED void inner(       double* result, const size_t  N,
                     const double* A,      const double* B,
                     sslot_t       done)
{
    double sum, *row_a, *column_b;
    sslot_t slot0 = init_sslot(0,0),
            slot1 = init_sslot(2,2);
THREAD-0:
    BLKMOV_SYNC(A, row_a,    N, slot1);
    BLKMOV_SYNC(B, column_b, N, slot1);
    sum = 0.0;
    END_THREAD();
THREAD-1:
    for (size_t i = 0; i < N; ++i)
        sum += row_a[i] * column_b[j];

    DATA_RSYNC(*result +=sum;, done);

    END_THREAD();

    END_FUNCTION;
}
```

Compilation Environment, Revisited



Compilation Environment, Revisited



Main Features of EARTH

- ∆ Fast thread context switching
- Efficient parallel function invocation
- Good support of fine-grain dynamic load-balancing
- ∆ Efficient support of split-phase transactions and fibers

Note—Items marked with a ∆ are features unique to EARTH, and not found in the original Cilk model

Outline

Summary of EARTH-C

Extensions

- Explicit parallelism
  - Parallel vs. sequential statement sequences
  - `forall` loops
- Locality annotation
  - Local vs. remote memory references (global, local, replicate, ...)
- Dynamic load-balancing
  - Basic vs. remote function & invocation sites

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