Compiling C for the EARTH Multithreaded Architecture

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Goals

1. Design simple high-level extensions for C that allow programmers to write programs that will run efficiently on multi-threaded architectures.
   (EARTH-C)

2. Develop compiler techniques to automatically translate programs written in EARTH-C to multi-threaded programs.
   (EARTH C $\rightarrow$ Threaded-C)

3. Determine if EARTH-C + compiler can compete with hand-coded Threaded-C programs.

EARTH C (Coarse Grain Parallelism)

Statement Sequences

Ordinary	`{  s1; s2; ...; sn  }`
Parallel	`{^ s1; s2; ...; sn ^}`
Sequential	`{! s1; s2; ...; sn !}`

Forall Loops

forall (*v* = *init_expr* **;**
test_expr **(** *v* **);**
v = *update_expr* **(** *v* **)**
)
loop_body **(** *v* **)**

Example:

```
forall (p=head; p != NULL; p = p->next)
  { f(p); }
```

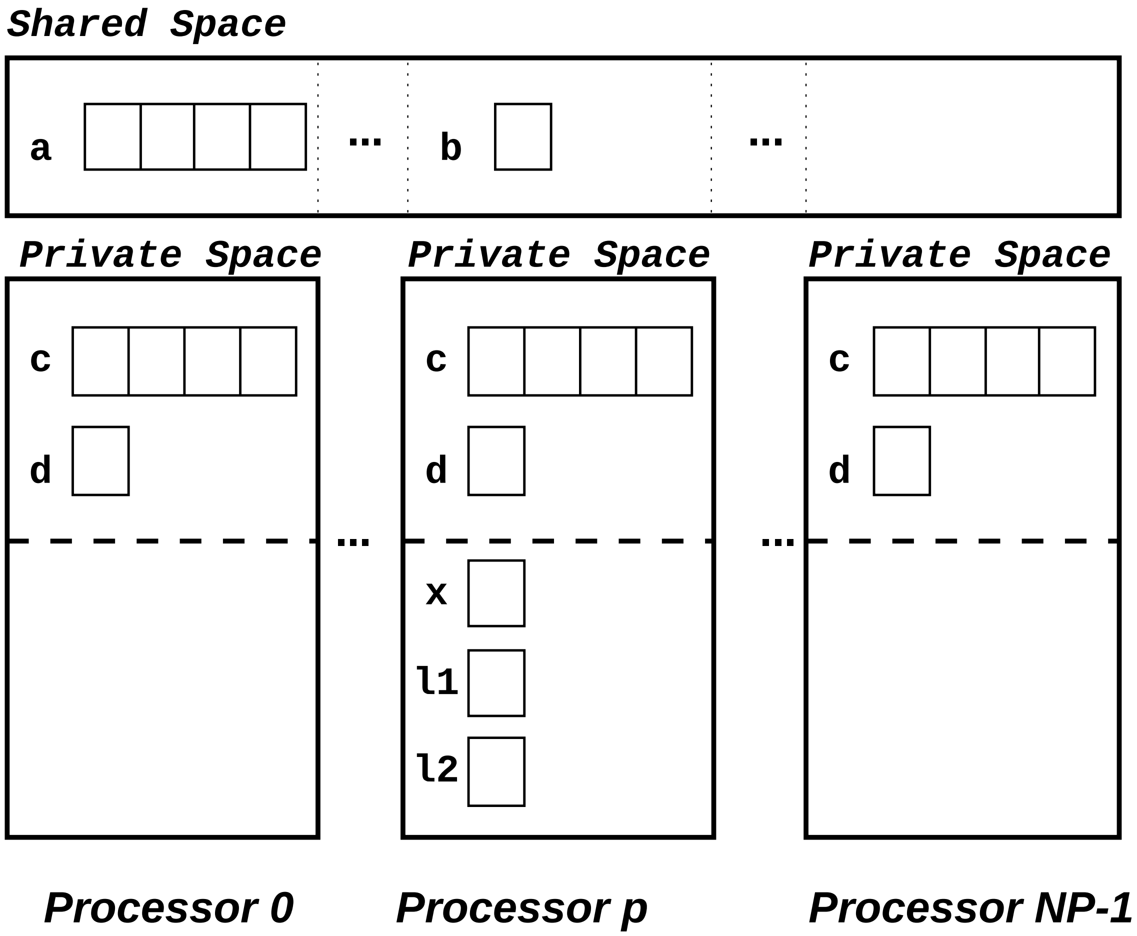
Remote Functions

- Function calls are assumed to remote, unless the function is declared as basic.
- Memory accesses in the function may be remote.
- An invocation `foo(a1,a2,..,an)` will be assigned to a processor by the run-time system. An invocation `foo(a1,a2,...,an)@my_exp()` will be assigned to the processor denoted by `my_exp()`.

Basic Functions

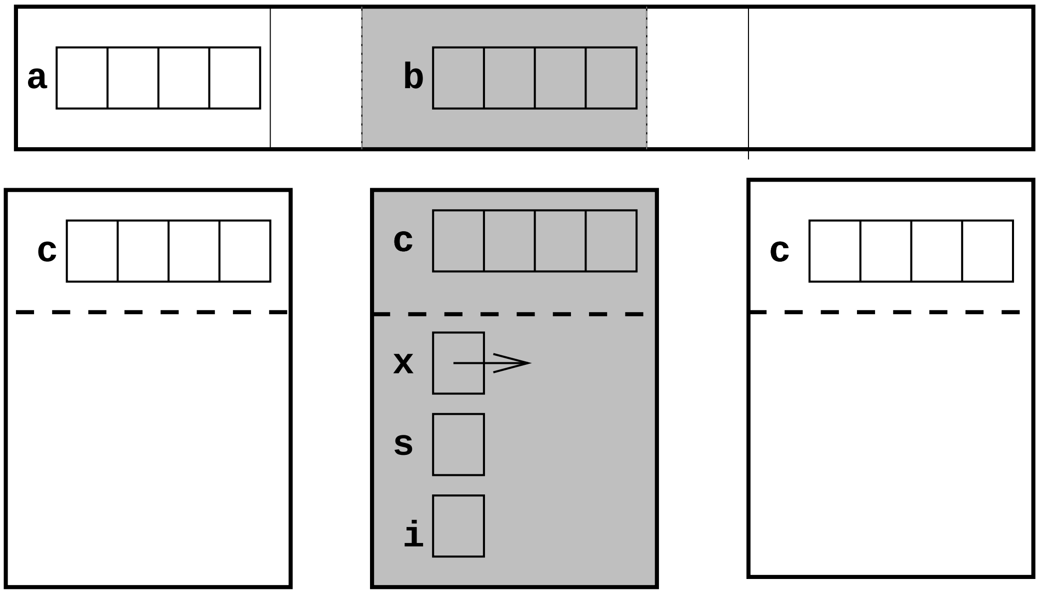
- `basic int foo() ...`
- All memory accesses in a basic function must be local.
- A call to a basic function will be executed on the processor that calls it.
- A basic function may be inlined.

Declarations and Memory Model




```
int a[4], b@p;
replicated int c[4], d;

foo(int x)
{ int l1, l2;
   ...
}
```

Pointers to Local Objects



Processor p

```
scale_vector(int *x, int s)
{ int i;
  for(i=0; i<10; i++)
    x[i] = x[i] * s;
}
```

```
scale_vector(a,10);
scale_vector(b,10)@ANY;
scale_vector(a,10)@myldbal();
```

```
lscale_vector(int local *x, int s)
{ int i;
  for(i=0; i<10; i++)
    x[i] = x[i] * s;
}
```

```
lscale_vector(c,20);
lscale_vector(b,10)@p;
lscale_vector(a,30)@OWNER_OF(a);
```

Summary of EARTH C Extensions

Declarations

```
replicated int x[10];
int a[100]@N;
int local * p;
basic foo ( ... ) { ... }
```

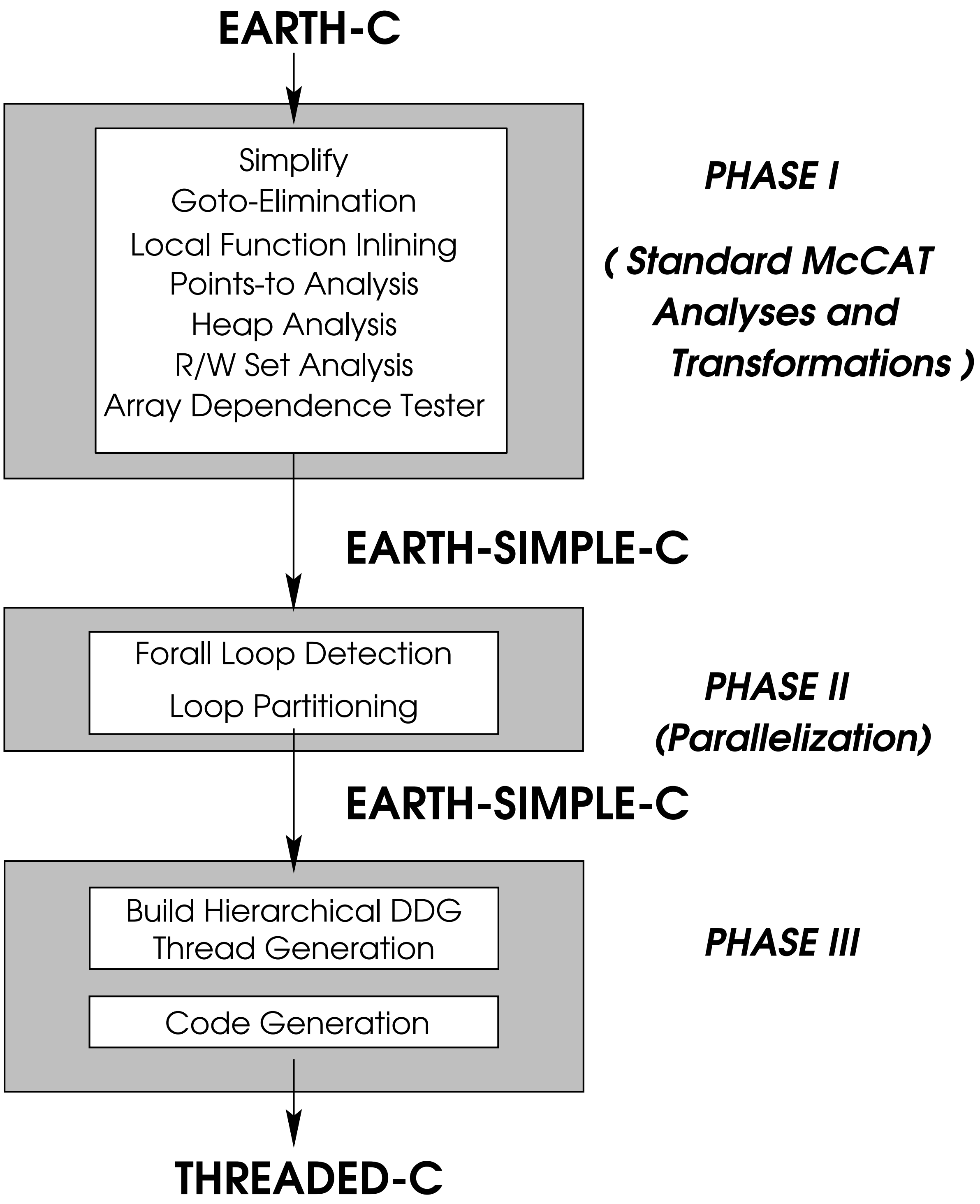
Control Constructs

```
{ ... }
{! ... !}
{^ ... ^}
forall(...) { ... }
p(...) @ OWNER_OF(x)
```

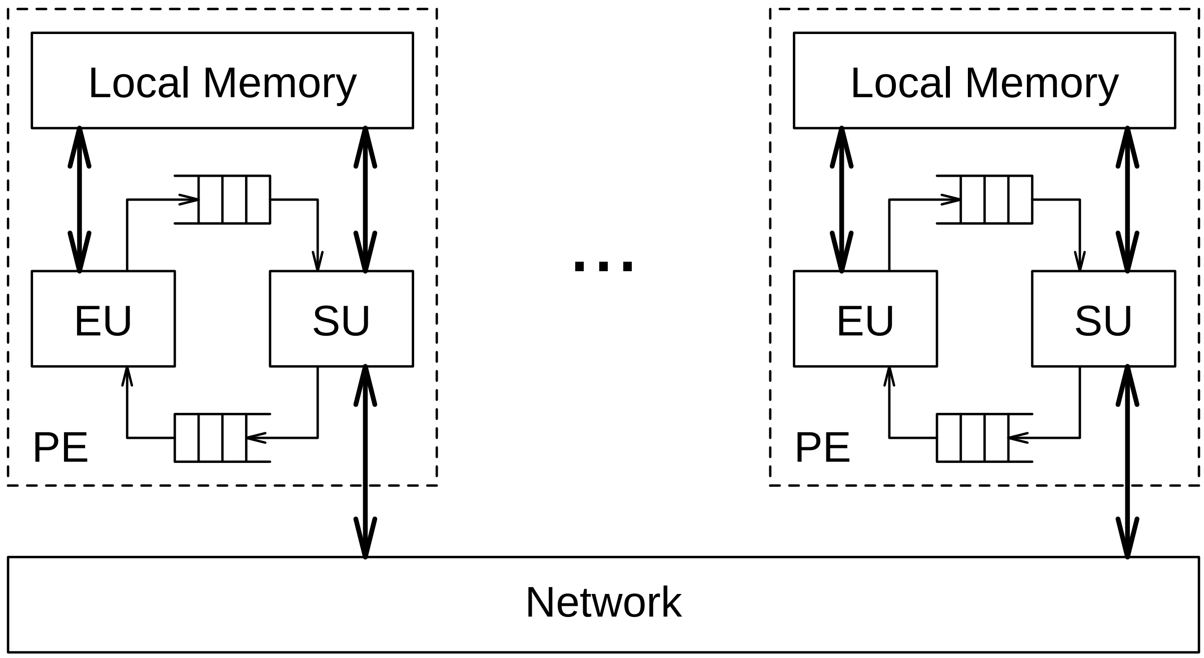
“Built-in” Const/Variables/Functions

```
#define ANY (-1)
replicated int NODE_ID;
int NUM_NODES;
MoveData(&A[i],buf,20)
OWNER_OF(A)
```

The McCAT/EARTH Compiler



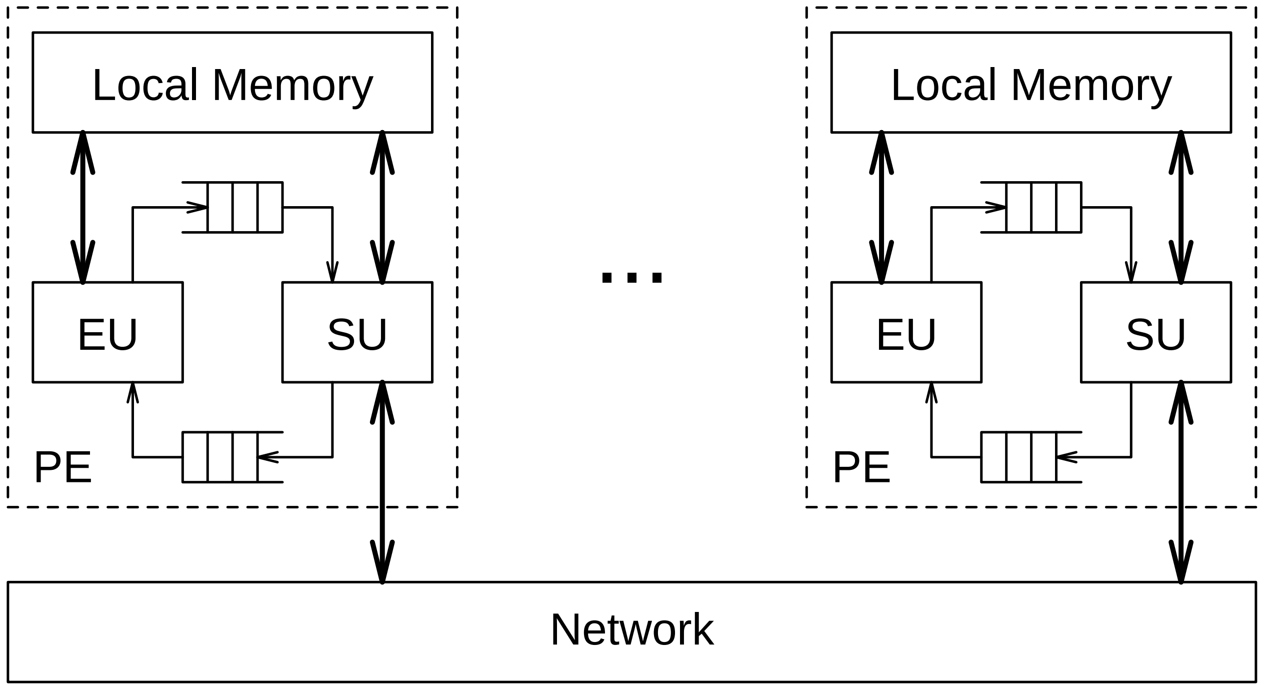
The EARTH Multithreaded Architecture (Model)



- The architecture consists of multiple EARTH nodes and an interconnection network.

- Each processing node consists of an *Execution Unit* (EU) and a *Synchronization Unit* (SU), which are linked together via buffers.

The EARTH Multithreaded Architecture (Model)



- The EU processes instructions of the active thread, until **completion** of the thread.

- The SU responds to synchronization commands, requests for data, and determines which threads are ready to run.

The EARTH Multithreaded Architecture (Testbed)

- Multithreaded emulator build on top of the GMD Manna parallel machine.

- Each processing node consists two Intel i860 CPUs, clocked at 50MHz, with 32 MB of dynamic RAM, and a bidirectional network interface capable of transferring 50MB/s in each direction.

- Efficient remote operations
  loading a remote word takes about 7μs
  calling a remote function about 9μs
  spawning a new thread about 4μs.

- Pipelining remote operations reduces the time to about 1/3rd.

EARTH C → Threaded C (Thread Generation)

Given a sequence of statements, $s_1, s_2, \ldots s_n$, we wish to create threads such that:

- maximize thread length (minimize thread switching overhead)

- retain *sufficient* parallelism

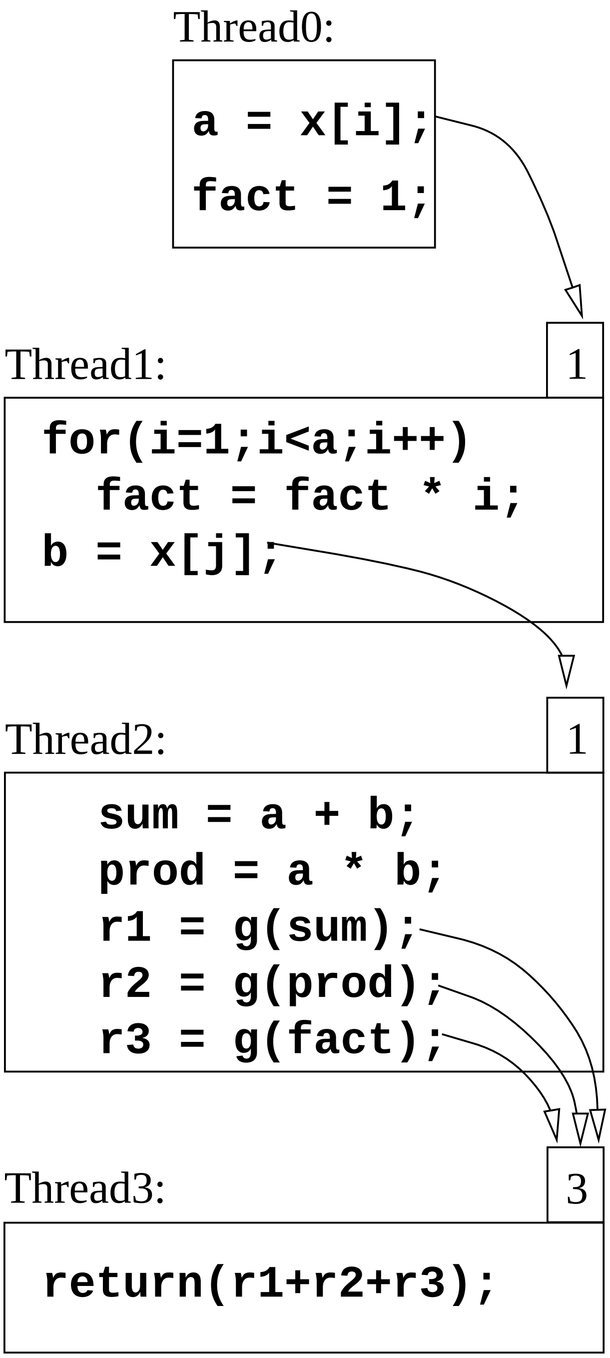
- issue remote memory requests as early as possible (prefetching)

- compile split-phase remote memory operations and remote function calls correctly

Example

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

  a = x[i];
  fact = 1;
  for(i=1; i<a; i++)
    fact = fact * i;

  b = x[j];
  sum  = a + b;
  prod = a * b;

  r1 = g(sum);
  r2 = g(prod);
  r3 = g(fact);

  return(r1 + r2 + r3);
}
```

Naive, Top-down Thread Generation



Better Strategy Using List Scheduling

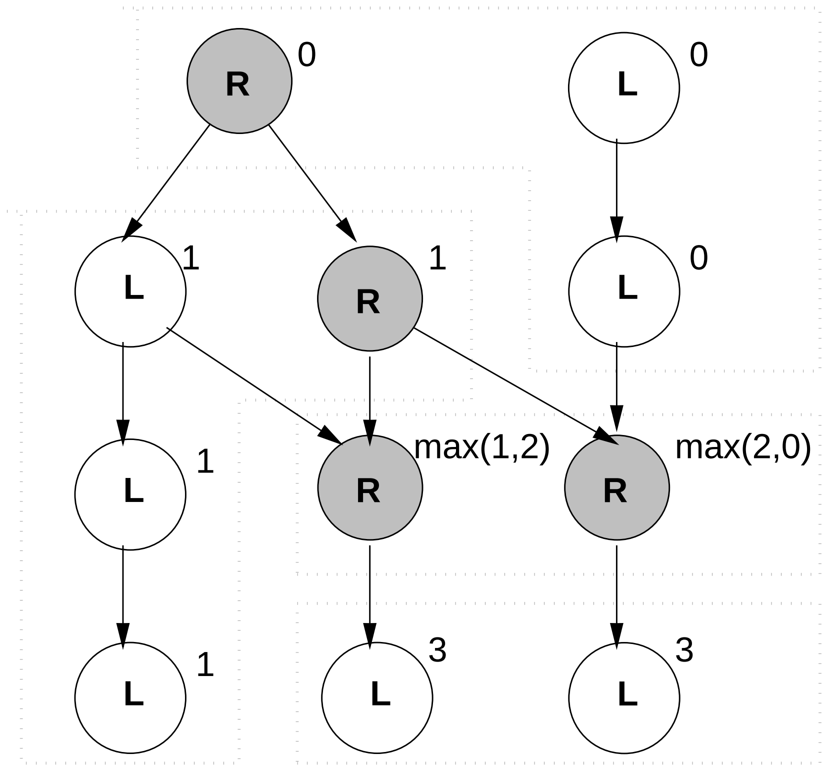
- Put each instruction in the **earliest** possible thread.
- Within a thread, put the remote operations are executed as early as possible.

Build a Data Dependence Graph (DDG), and use a list scheduling strategy, where the selection of instructions is guided by *Earliest Thread Number* and *Statement Type*.

Earliest Thread Number

If instruction Q has n remote ancestors, $P_1 \ldots P_n$, then the earliest possible thread for Q is:

$$1 + max(tnum(P_1), \ldots, tnum(P_n)).$$



Instruction Types

SCHEDULE FIRST

REMOTE_READ,REMOTE_WRITE

REMOTE_FN_CALL

LOCAL_SIMPLE

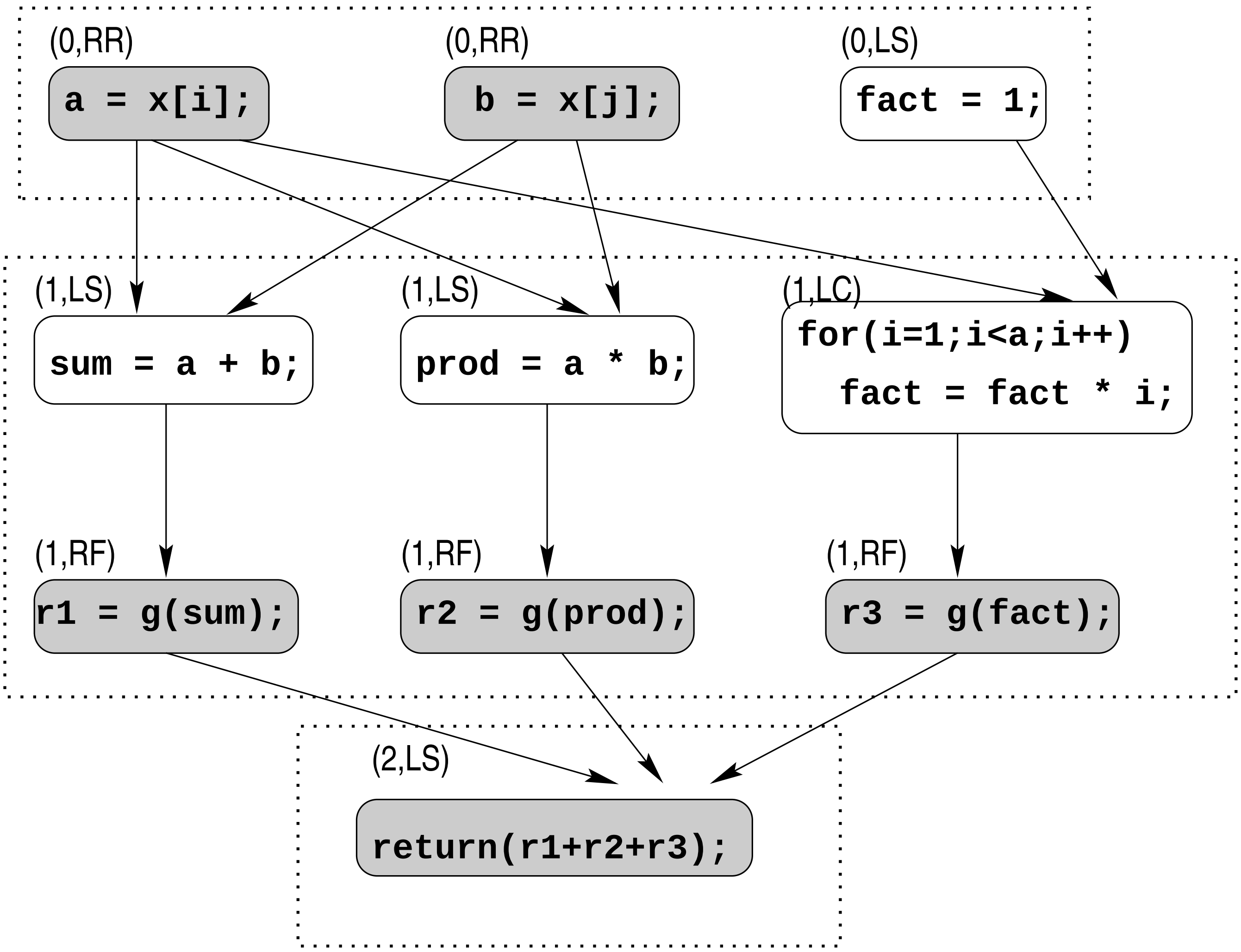
REMOTE_COMPOUND

LOCAL_COMPOUND

BASIC_FN_CALL

SCHEDULE LAST

List Scheduling Previous Example



Resulting List-scheduled Threads

Thread0:

```
a = x[i];
b = x[j];
fact = 1;
```

Thread1: 2

```
sum = a + b;
r1 = g(sum);
prod = a * b;
r2 = g(prod);
for(i=1;i<a;i++)
  fact = fact * i;
r3 = g(fact);
```

Thread2: 3

```
return(r1+r2+r3);
```

Generating Threaded-C Code

```
THREADED f(int *ret_parm, SLOT *rsync_parm,
           int *x, int i, int j)
{ SLOTS SYNC_SLOTS[2];
  int a,b,sum,prod,fact, r1,r2,r3;

/* THREAD_0:; */
  INIT_SYNC(0, 2, 2, 1); INIT_SYNC(1, 3, 3, 2);
  GET_SYNC_L(&x[i], &a, 0);
  GET_SYNC_L(&x[j], &b, 0);
  fact = 1;
  END_THREAD();
THREAD_1:;
  sum = a + b;
  TOKEN(g, &r1, SLOT_ADR(1), sum);
  prod = a * b;
  TOKEN(g, &r2, SLOT_ADR(1), prod);
  for (i = 1;i < a; i = i + 1)
    { fact = fact * i; }
  TOKEN(g, &r3, SLOT_ADR(1), fact);
  END_THREAD();
THREAD_2:;
  DATA_RSYNC_L(r1+r2+r3, ret_parm, rsync_parm);
  END_FUNCTION();
}
```

Experimental Results

- Develop three versions of each benchmark:

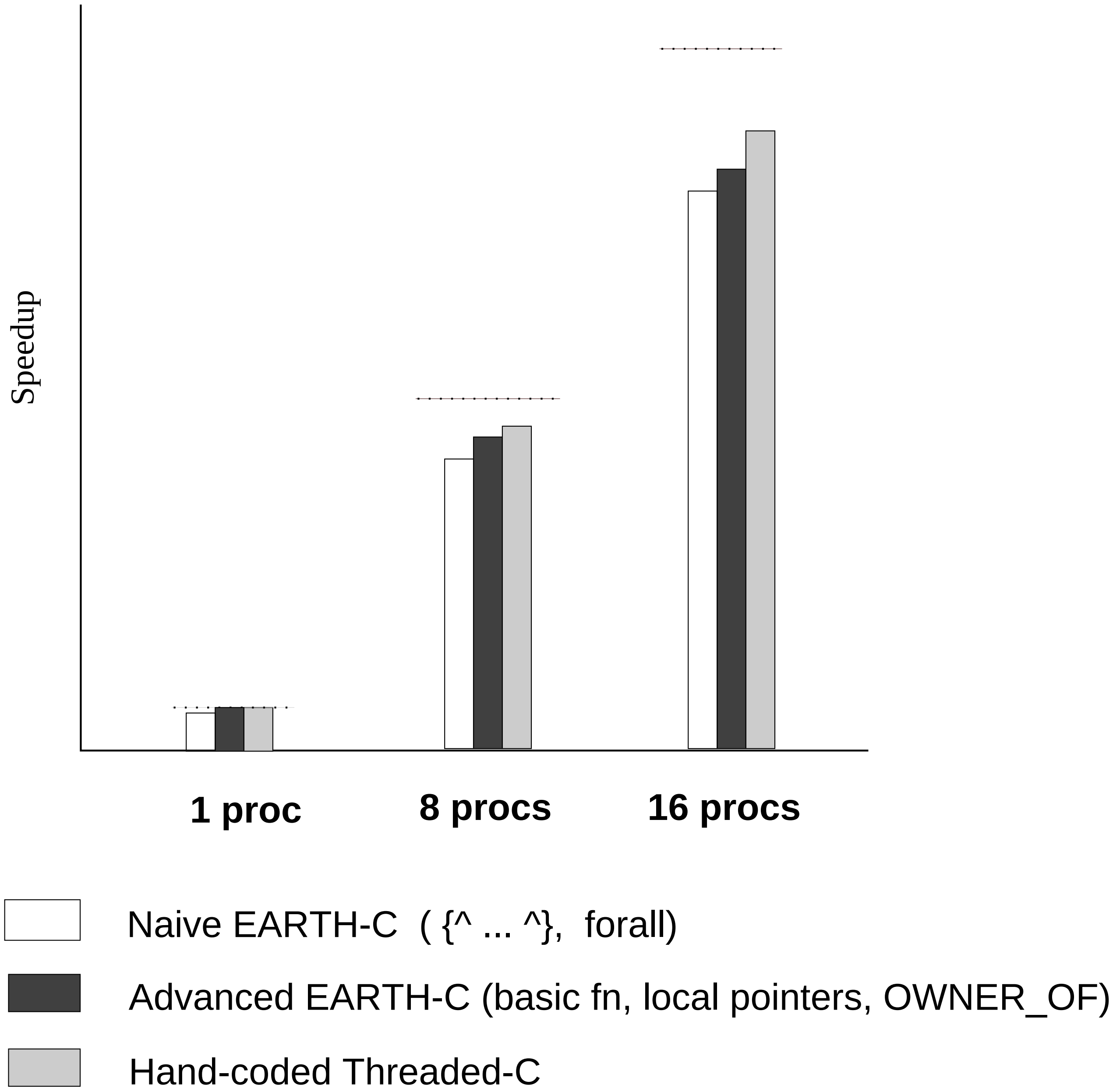
  Naive EARTH-C: Develop a simple parallel version of the program using relatively few EARTH-C constructs.

  Advanced EARTH-C: Improve the performance of the program by using more advanced EARTH-C features like local pointers and basic functions to enhance data locality.

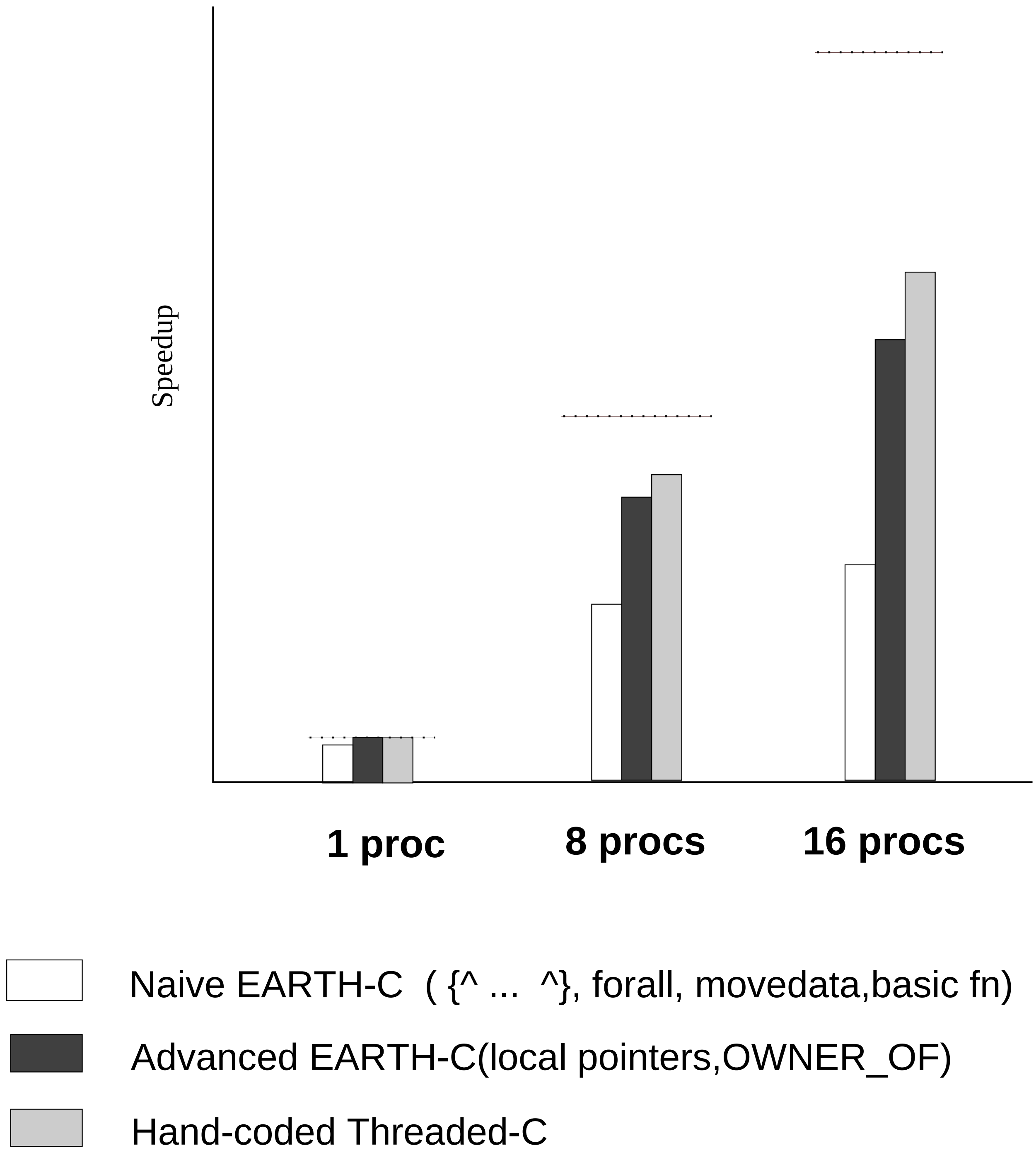
  Hand-coded Threaded-C: The best existing hand-coded parallel program.

- Can we approach the performance of the hand-coded Threaded-C programs, using only EARTH-C + McCAT/EARTH compiler?

Power Benchmark (k-ary tree with 10,000 leaves)



Heuristic TSP Benchmark (32K cities)



What's new and what's not

- There are many related C dialects that are targeted to multi-threaded archtectures including SPLIT-C, Cid, Cilk,EM-C.

- EARTH-C is different in that the language is intended to be very simple, and does **NOT** expose multithreading to the user.

- The McCAT/EARTH compiler is different in that it uses dependence analysis (including pointer analysis) plus information provided via EARTH-C constructs to automatically generate low-level threaded programs.

- We have developed the language and compiler in conjunction with the architecture and run-time system.

Ongoing and Future Work

- further refinements to EARTH-C, motivated by our experiences with more applications (shared variables and atomic functions)

- develop more sophisticated thread generation strategies based on a cost model

- design new pointer analyses that can infer locality information, and automatically produce specialized functions

- continue to experiment with new applications.