Cilk 2.0 Reference Manual[1]

July 10, 1995

[1]Cilk is trademark of the Massachusetts Institute of Technology. The Cilk project has been partially supported by ARPA contracts N00014-94-1-0985 and N00014-92-J-1310. Computer time on the CM5 was provided by the Scout project under ARPA contract MDA972-92-J-1032.

Contents

1 Introduction **4**
- 1.1 What is Included in Cilk 2.0 . . . 4
- 1.2 Background and Goals . . . 4
- 1.3 The Cilk Model of Multithreaded Computation . . . 5
- 1.4 Ongoing and Future Work . . . 7
- 1.5 About This Manual . . . 8

2 Programming in Cilk **9**
- 2.1 Getting Started . . . 10
  - 2.1.1 Compiling and Running Cilk Programs . . . 12
- 2.2 Writing Simple Cilk Programs . . . 13
  - 2.2.1 Procedures . . . 13
  - 2.2.2 Sequential Calls . . . 14
  - 2.2.3 The first Cilk procedure: `cilk_main` . . . 15
  - 2.2.4 Standard Runtime System Options . . . 16
- 2.3 Passing Arrays to Procedures . . . 17
- 2.4 Threads and Explicit Continuation-Passing . . . 19
  - 2.4.1 Spawning Threads from a Procedure, and Vice Versa . . . 21
  - 2.4.2 Accumulators . . . 22
  - 2.4.3 Signals . . . 23
  - 2.4.4 Direct and Tail Calling Threads . . . 24
  - 2.4.5 Pass-by-value Array Arguments to Cilk Threads . . . 24
  - 2.4.6 Migration Threads . . . 25
- 2.5 More Advanced Techniques . . . 27
  - 2.5.1 Overriding Work-Stealing . . . 27
  - 2.5.2 Handler Threads . . . 28
  - 2.5.3 Entering the Scheduler from a SPMD Computation . . . 28
  - 2.5.4 Data Structure Primitives . . . 29
  - 2.5.5 Manual Scheduling in Cilk . . . 30

3 Language Reference **33**
- 3.1 Basic Concepts . . . 33
  - 3.1.1 Closures and Continuations . . . 33
  - 3.1.2 Frames . . . 34

3.1.3 Runtime Scheduling and Work Stealing . . . 34
3.2 Program Structure . . . 35
3.3 Keywords . . . 35
3.4 Types . . . 36
3.5 Procedure/Thread Definitions and Declarations . . . 36
3.6 Spawning . . . 37
3.7 Passing Arguments and Returning Values . . . 37
3.7.1 Passing Array Arguments by Value . . . 38
3.7.2 Continuation Capturing Arguments . . . 39
3.7.3 Thread Communication Primitives . . . 40
3.7.4 Continuation Arithmetic . . . 40
3.8 Synchronization . . . 41
3.9 Sequential Execution . . . 41
3.9.1 Sequential Execution of Procedures . . . 41
3.9.2 Direct and Tail Calling Threads . . . 42
3.9.3 Notes on Argument Passing . . . 42
3.10 Annotations for Thread Scheduling . . . 43
3.11 Migration Threads . . . 43

A Copyright and Disclaimers **46**

B Installation Instructions **47**
B.1 Finding Cilk at MIT . . . 47
B.2 How to Obtain Cilk . . . 47
B.3 How to Install Cilk . . . 47
B.4 How to run the regression tests . . . 48
B.4.1 Strata regression test . . . 48
B.4.2 Cilk run-time system regression test . . . 48
B.4.3 Running the Cilk examples . . . 48
B.5 Mailing Lists . . . 48
B.6 Reporting Bugs . . . 48

C The Cilk Preprocessor **49**

D Specification of the Cilk Runtime System **52**
D.1 Errata . . . 52
D.2 Introduction . . . 52
D.3 Data Types and Constants . . . 54
D.4 Procedures . . . 55

E Cilk Runtime System Implementor's Guide **70**
E.1 First step: get a sequential version of Cilk running . . . 70
E.2 Second step: get a work-stealing scheduler running . . . 73
E.3 Step three: add time statistics . . . 76

F Notes on Compiling Cilk **78**
F.1 Notes to Cilk 1.x Users 78
F.2 Closures and Frames 78

G Release Notes **81**
G.1 Release 2.0 Beta 1 81
G.2 Release 1.2 Beta 1 81
G.3 Release 1.1 Beta1 82
G.4 Release 1.0 Beta2 82

H Language Changes **83**
H.1 From Version 1.2 to 2.0 83
H.1.1 Major Changes 83
H.1.2 Minor Changes 86

I People **89**

Chapter 1

Introduction

This document describes Cilk 2.0, an ANSI C-based language and runtime system for multithreaded programming. Cilk is designed for computations with dynamic, highly asynchronous, tree-like parallelism, which are typically difficult to write in data-parallel or message-passing style. Divide-and-conquer algorithms and backtracking search are examples of tree-like computations that are particularly well-suited to Cilk.

1.1 What is Included in Cilk 2.0

This release includes the Cilk runtime system, the Cilk-to-C preprocessor (cilk2c), a collection of example programs, and this manual.

The Cilk runtime system included in this release runs on two multiprocessor platforms: the Thinking Machines CM-5 and the Sun Sparc SMP. It also runs on uniprocessors running Unix or Linux.

Cilk has been ported to other platforms not included in this release: PVM, the Intel Paragon, the SGI Power Challenge SMP, and networks of workstations. For more information about these implementations, or for help with porting Cilk to a new platform, contact the Cilk group by sending electronic mail to `cilk-developers@theory.lcs.mit.edu`.

1.2 Background and Goals

Cilk is designed to support dynamic, tree-like parallelism on message-passing architectures. The philosophy behind Cilk is that a programmer should concentrate on structuring a program to expose parallelism, while the runtime system dynamically schedules the computation to run efficiently on any number of processors. The runtime system takes care of details like load balancing and communication protocols.

Cilk grew out of work in both theory and implementation. The theoretical input to Cilk comes from a study of scheduling multithreaded computations, and especially of the performance of work-stealing, which provided a scheduling model that has since been the

[1]This chapter was written by Yuli Zhou and Rob Miller.

central theme of Cilk development. These results led to the development of a performance model that accurately predicts the efficiency of a Cilk program using two simple parameters: work and critical path [BJK+95, BL94].

The first implementation of Cilk was a direct descendent of PCM/Threaded-C, a C-based package that provided continuation-passing-style threads on the CM-5 and used work-stealing as a general scheduling policy to improve the load balance and locality of the computation [HZJ94a, HZJ94b].

The latest release, Cilk 2.0, shows significant improvements. The language is now fully typechecked, supports all of ANSI C in its C-language subset, and offers a simpler syntax for writing multithreaded procedures. The runtime system has been made more portable, and the base release includes support for several architectures other than the CM-5. The provably-efficient scheduler has been incorporated into the runtime system, and many performance improvements have been made.

A key principle in the Cilk development methodology is that the runtime mechanisms and language features are closely tied to the development of practical applications. To date, major applications developed in Cilk include graphics rendering, protein folding [PJGT], backtracking search, and the *Socrates chess program [JK94], which won 3rd place in the 1994 ACM ICCC (International Computer Chess Championship), and recently won 2nd place in the 1995 ICCC.

1.3 The Cilk Model of Multithreaded Computation

A Cilk program consists of a collection of "procedures," where each procedure is broken down into multiple "threads." For example, here is a Cilk procedure that computes the nth Fibonacci number:

```
cilk int fib (int n)
{
    if (n < 2) return (n);
    else
    {   int x, y;

        x = spawn fib (n-1);
        y = spawn fib (n-2);

        sync;
        return (x+y);
    }
}
```

In the body of the procedure, the `spawn` statements invoke recursive calls to `fib` via the scheduler, which may execute them in parallel and possibly on different processors. The `sync` statement suspends a procedure until all of its spawned child procedures return, so that their return values can be used afterwards.

In Cilk terminology, a *thread* is a sequence of non-blocking code within a procedure. A procedure is divided into threads by the `sync` statements. The thread that starts the procedure is called the *initial thread*, and threads that start after a `sync` are called *successor threads*. At runtime, the spawn relationships between procedures form a tree, and the data dependencies among their threads form a dag. This is illustrated in Figure 1.1.

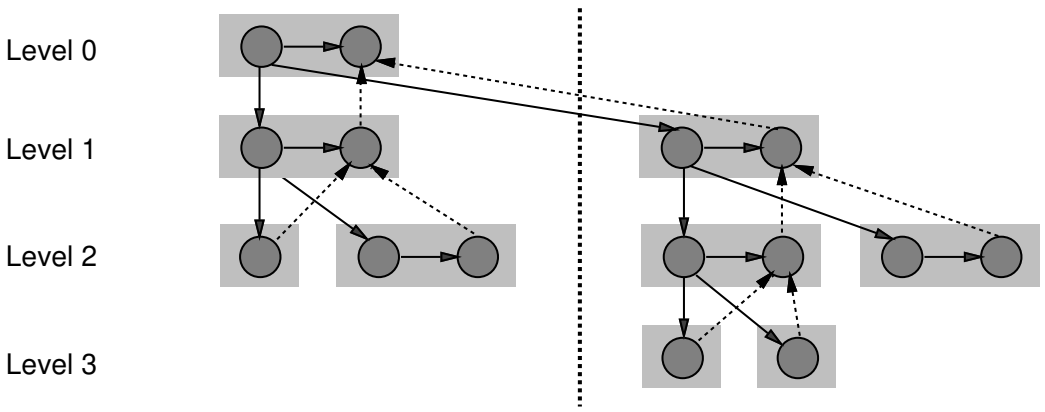


Figure 1.1: The Cilk model of multithreaded computation. Threads, shown as circles, are grouped into procedures, shown as shaded rectangles. Downward solid edges indicate procedure spawning, horizontal solid edges indicate continuation to successor threads, and upward dashed edges indicate returning values to parent procedures. All three types of edges are data dependencies which constrain the order in which threads may be executed.

A correct execution of a Cilk program must obey all the data dependencies in the dag, since a thread cannot be executed until all the threads it depends on have completed. For a program containing parallelism, however, the data dependencies form only a partial order, permitting many ways of scheduling the threads in the dag. In actual implementation, the order in which the dag unfolds and the mapping of threads onto processors are crucial decisions. Every active procedure has associated state that takes up storage, and every data dependency between threads assigned to different processors requires communication. Thus, different schedules may have drastically different effects on the space and time efficiency of the computation.

It can be shown that for general dags, no good scheduling policy exists, in the sense that a dag can be constructed for which any schedule providing linear speedup requires more than linear expansion of space [BL94]. The problem can be solved by restricting the class of dags to those generated by *strict* computations, where a spawned procedure only sends values to its own ancestors in the spawning tree. A subclass of strict computations, called *fully strict* computations, is especially interesting in that a procedure only sends values to its parent. Since this reflects exactly the ordinary procedure call-return semantics, all dags formed by Cilk procedures are fully strict.

The Cilk runtime system implements a general scheduling policy based on *work-stealing*. In work-stealing, the work of a computation is distributed dynamically among all the processors involved in the computation. Locally, a processor executes procedures in sequential

order, working depth-first through the dag. Spawned procedures are placed in a ready queue until the scheduler can execute them. When a processor has no work to do, it steals a ready procedure from another processor chosen at random. Thus, work-stealing balances the load in distributed, probabilistic fashion.

Cilk's work-stealing scheduler executes a fully strict computation in time and space close to optimal. From a theoretical perspective, there are two fundamental limits to how fast a Cilk program can run. The first limit is the amount of *work* in the program, or the total time needed to execute all threads in the dag, which we equate with the program's uniprocessor execution time and denote by T_1. The second limit is the program's *critical path*, or the time needed to execute threads on the longest path of data dependency, which we equate with the program's execution time on an infinite number of processors and denote by T_∞. Cilk's work-stealing scheduler executes a fully strict computation on p processors in time $O(T_1/p + T_\infty)$, which is optimal. In practice the constant factor has been measured very close to 1 [BJK+95]. Thus, for programs with plenty of parallelism ($T_1/T_\infty \gg p$), the Cilk scheduler provides linear or nearly linear speedup.

From an implementation perspective, we all know that the sequential execution (i.e., depth-first schedule) of the dag is both space efficient and has good locality. The Cilk scheduler is simply running multiple sequential computations, one on each processor. Assuming S_1 to be the space required for the sequential execution on one processor, a p-processor execution thus requires no more than $S_1 p$ space, or the equivalent of one runtime stack per processor.

To this end, the Cilk runtime system sorts the ready procedures on a processor in order of their level in the spawning tree (see Figure 1.1). Locally, a processor executes procedures in depth-first order, always executing a procedure from the deepest level of the spawn tree. When another processor requests work, however, the processor gives it a ready procedure from the *shallowest* level of the tree, since procedures at shallower levels represent more work. In addition, the last returning child that enables its parent procedure migrates the parent to its own processor for execution, in keeping with the "one stack per processor" invariant.

1.4 Ongoing and Future Work

Recent versions of Cilk have concentrated on runtime dynamic scheduling, leaving out an important aspect of parallel programming: globally shared data structures. We have developed a theoretical model and implementation of a shared memory system which is consistent with Cilk's goals of preserving locality and minimizing overhead. The next release of Cilk is expected to include this shared memory system, along with new language features that make it convenient to use.

The next release of Cilk is also expected to include more sophisticated synchronization and control mechanisms for Cilk procedures. With *inlets*, a procedure will be able to specify some work that is performed as soon as a spawned child returns, such as spawning off additional children, or even prematurely terminating the remaining children. This mechanism will enable Cilk procedures to perform various kinds of speculative computation which in the current Cilk release can only be achieved by explicit continuation-passing (threads).

Another project that will soon come to fruition is Cilk-NOW, a portable system for scheduling Cilk programs on a network of idle workstations [BP94]. Cilk-NOW is dynamic, fault-tolerant, and adaptive. Workstations can enter and leave the parallel computation at any time without disruption, and a Cilk job's share of the available workstations changes dynamically with the job's changing level of parallelism. The initial release of Cilk-NOW is expected soon.

1.5 About This Manual

This manual is primarily intended for users who wish to write Cilk application programs. It also serves as documentation for implementors who wish to port Cilk to other platforms. Chapter 2 is a programmer's guide and introduces various features of the Cilk language and runtime system interface. Chapter 3 is a reference for the Cilk language. The appendices provides a complete specification of the Cilk runtime system, a guide to porting the Cilk runtime system, and some miscellaneous documentation of this Cilk distribution.

Chapter 2

Programming in Cilk

This chapter introduces the Cilk language from a programmer's perspective. It shows how to write, compile, and run a simple Cilk program, then describes in more detail the language features that a beginning Cilk programmer needs to understand. We assume that the reader is already familiar with C.

Figure 2.1 shows the structure of the Cilk system (for the CM-5). An application programmer writes a Cilk program, which is transformed to ordinary C code by the Cilk preprocessor `cilk2c`, and then compiled and linked with the runtime system using the C compiler on the target machine. During execution, the runtime system uses native message-passing facilities on the parallel machine to schedule, communicate, and synchronize the threads in the program. On the CM-5, for example, the runtime system uses Strata, a basic message-passing library that supports efficient active messages. Cilk has also been implemented on shared-memory architectures by simulating message-passing.

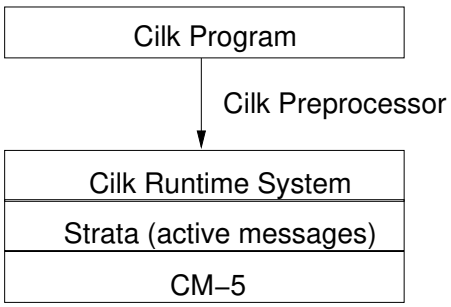


Figure 2.1: Overall structure of the Cilk package on the Thinking Machines CM-5

[1]This chapter was written by Yuli Zhou and Rob Miller.

2.1 Getting Started

The first code we are going to write in Cilk is a program that computes the Fibonacci function recursively. In C, this program could be written as shown in Figure 2.2.

```
#include <stdlib.h>
#include <stdio.h>

int fib (int n)
{
    if (n<2) return (n);
    else
    {   int x, y;

        x = fib (n-1);
        y = fib (n-2);

        return (x+y);
    }
}

int main (int argc, char *argv[])
{
    int n, result;

    n = atoi(argv[1]);
    result = fib (n);

    printf ("Result: %d\n", result);
    return 0;
}
```

Figure 2.2: Sequential C program that computes the Fibonacci function.

In comparison, Figure 2.3 shows a Cilk program that computes the Fibonacci function. Notice how similar the two programs look. In fact, the only differences between them are an extra include file (`cilk.h`) and a few keywords: `cilk`, `spawn`, `sync` and `cilk_main`. The `cilk` keyword identifies a Cilk procedure. Within a procedure, other procedures can be `spawn`'d to create parallel threads of execution, and the `sync` statement waits for all spawned procedures to come back so that their return values can be used. The procedure `cilk_main` is the first procedure executed in a Cilk program. These keywords and others will be described in more detail in section 2.2. But first, we will compile and run this simple Cilk program.

```
#include <stdlib.h>
#include <stdio.h>
#include <cilk.h>

cilk int fib (int n)
{
    if (n<2) return n;
    else
    {   int x, y;

        x = spawn fib (n-1);
        y = spawn fib (n-2);

        sync;
        return (x+y);
    }
}

cilk int cilk_main (int argc, char *argv[])
{
    int n, result;

    n = atoi(argv[1]);
    result = spawn fib(n);

    sync;
    printf ("Result: %d\n", result);
    return 0;
}
```

Figure 2.3: Cilk program that computes the Fibonacci function.

2.1.1 Compiling and Running Cilk Programs

Depending on your target machine, the steps involved in compiling and running Cilk programs may be different. The following instructions are specific to the CM-5. We assume some basic knowledge of Unix and C program development on the CM-5.

Cilk program files, which end with `.cilk` by convention, are first transformed to ordinary C code by the Cilk preprocessor `cilk2c`, producing `.c` files. The resulting C program files are compiled using the C compiler and linked with the Cilk runtime library. The easiest way to get started is to use the standard makefile included in the `examples` directory of the Cilk distribution, which automates all of these steps.

The source code for Fibonacci in Cilk may be found under the name `fib.cilk` in the `examples` directory of the Cilk distribution. After installing the distribution[2], you can simply type:

```
cm5> make fib_cm5_st
```

to make the executable. The `_cm5` extension is used to denote executables that run on the CM-5, and the `_st` extension is for executables with statistics gathering enabled. To run the program, type

```
cm5> jrun fib.job
```

to execute `fib_cm5_st` on the CM-5, using the DJM job script `fib.job` to request an appropriate machine partition.

At the end of the execution, you should see a printout similar to the following:

```
+ fib_cm5_st -nproc 32 30
fib (30) running on 32 processors
Result: 832040
32 processors participating, execution time 2.384271 seconds
PE     Local/ Stub Migratd Clos  Queue   Heap  Lev Requests
-------------------------------------------------------------
 0:   126557/   41     119   64     32    887   29     4979
31:   126495/   86     134   29     13    418   29      523
...
PE      Work    Sched  Polling     Term    Other    Total  Broken
-------------------------------------------------------------------
 0:   1.3012   0.8347   0.2844   0.0007   0.0049   2.4258       1
21:   1.2720   0.8672   0.2819   0.0012   0.0032   2.4256       1
...
Critical path: 0.015099 seconds
```

[2]If you are using `scout` at MIT, on which the Cilk distribution is already installed, it is only necessary to make a copy of the `examples` directory. Make sure that the `STRATA_DIR` and `CILK_DIR` assignments in the `Makefile` point to each of their distribution directories respectively (see chapter B.1 for the locations of these directories).

After the output of the program itself ("Result: 832040"), the runtime system reports several useful statistics collected during execution. The first line of statistics gives the number of active processors and the overall execution time. Next is a table that reports the numbers and sizes of key data structures in the Cilk runtime environment. Following that comes another table giving a breakdown of the overall execution time spent on various activities, plus an indicator (`Broken`) of the accuracy of the timing statistics.[3] The last line reports the critical path length of the program.

These numbers reveal some common patterns in the dynamic execution of Cilk programs. Of all the threads executed on each processor (`Local`), work-stealing migrates only a small number of them (`Migratd`). The number of closures (i.e., activation frames of procedures) that are allocated at any time (`Clos`) is fairly small, as is the size of the ready queue (`Queue`), reflecting the moderate space requirements due to Cilk's "one sequential computation per processor" model. (Note that we invoked the `fib` procedure with an argument of 30, so a sequential computation would use a stack at most 30 activation records deep. The `Clos` and `Queue` statistics are within a small constant factor of the sequential space requirements.)

The claim that work-stealing is an effective way of load-balancing among processors is reflected in the roughly equal work time (`Work`) on each processor, achieved with relatively few requests to steal work (`Requests`). Since the threads in the `fib` procedure are quite short, the scheduler overhead (`Sched`) is significant compared to work time, but the overhead-to-work ratio would be very small with sufficiently long threads.

The critical path of the Fibonacci program is very short (0.015 seconds compared to 2.38 seconds of 32 processor execution time). The Cilk performance model (see section 1.3) thus predicts near linear speedup over one-processor execution time. To verify if this is really the case, you can modify the `fib.job` script to run the program on various numbers of processors, specified by the `-nproc` option.

2.2 Writing Simple Cilk Programs

A Cilk program is made up of Cilk procedures and ordinary C functions. As we described in section 1.3, a procedure is further broken down to threads, which are the basic units of scheduling. Actually, the Cilk language also supports the abstraction of threads (see section 2.4), which can be used to access the capabilities of the runtime system directly. However, for simple programming tasks the procedure abstraction should prove to be both sufficient and much easier to work with.

2.2.1 Procedures

A procedure is the parallel equivalent of a C function. It may spawn other procedures in parallel and contain synchronization points. A procedure definition is identified by the keyword `cilk`, and has an argument list and body just like a C function. The following is the `fib` procedure shown previously:

[3] The `Broken` columns counts the number of "broken" threads – threads which are interrupted by a context switch on the CM-5.

```
cilk int fib (int n)
{
    if (n<2) return n;
    else
    {   int x, y;

        x = spawn fib (n-1);
        y = spawn fib (n-2);

        sync;
        return (x+y);
    }
}
```

The actual work in a Cilk procedure is performed by ordinary C code, which is executed sequentially. Parallelism is created when a procedure is spawned. Spawning a procedure creates an activation frame for the procedure, which is subsequently managed by the scheduler. The programmer specifies neither where nor exactly when the procedure will be executed. It is up to the scheduler to execute it at some later time, and possibly on a different processor.

A procedure cannot use the return values of the procedures it has spawned until it executes a `sync` statement to wait for all of them to return. The `sync` statement is the point where the current thread of the procedure terminates, and the scheduler suspends the current procedure and performs other work. When all of the child procedures return, execution of the procedure resumes at the point right after the `sync` statement, which starts a successor thread.

Spawns and syncs expose the parallelism in a program, without specifying how the parallel threads should be scheduled. This separation of parallelism from actual scheduling decisions is critical to Cilk, whose runtime system depends on work-stealing to dynamically migrate procedures among processors for load balancing. We have already explained in section 1.3 why such a generic scheduling policy works well for fully strict programs, which at this point includes all Cilk programs written in procedure style.

In practice, work-stealing works best with "bushy" spawning trees, where each procedure spawns only a few children. Bushy spawning trees are better because each steal carries a large amount of work, which minimizes the number of procedures migrated by work-stealing. In contrast, a procedure which spawns hundreds of children in a tight loop, where each child has only a small amount of work to do, executes very poorly in the work-stealing model. The same program could be restructured in a more tree-like manner, so that the original procedure spawns two procedures, which in turn spawn two procedures, and so on until the leaves of the computation are reached. The restructured program should perform much better under work-stealing.

2.2.2 Sequential Calls

Every Cilk procedure has a "sequential version," an equivalent C function which can be executed with the special keyword `call`. The sequential version is derived from the procedure

by removing all `sync` statements and changing all `spawn`s to `call`s. Calling a procedure sequentially has much lower overhead than spawning it in parallel (by about an order of magnitude), so this feature is useful when the procedure body is expected to execute quickly. For example, one may wish to call `fib` sequentially once the argument drops below 10:

```
cilk int fib (int n)
{
    if (n < 2) return(n);
    else if (n < 10) return (call fib (n-1) + call fib (n-2));
    else
    {   int x, y;

        x = spawn fib (n-1);
        y = spawn fib (n-2);

        sync;
        return (x+y);
    }
}
```

When a procedure is called sequentially, all computation within that procedure is also executed sequentially, including all of its child procedures and their descendents. Thus, every sequential call reduces the amount of parallelism in the Cilk program, so these calls should be used with care. Sequential calls are very useful for testing and debugging, however, since a sequential computation is completely deterministic. The standard Cilk option `-serial` causes the entire Cilk program to run serially by calling the sequential version of `cilk_main`.

2.2.3 The first Cilk procedure: `cilk_main`

The procedure `cilk_main` is treated specially by the Cilk preprocessor, which generates initialization code that makes it the first procedure executed by the scheduler. Like the C `main` function, `cilk_main` has the prototype

```
cilk int cilk_main (int argc, char *argv[]);
```

and receives the command line arguments as its parameters. For example, here is the definition for `cilk_main` in the Fibonacci program:

```
cilk int cilk_main (int argc, char *argv[])
{
    int n, result;

    n = atoi(argv[1]);
    result = spawn fib(n);

    sync;
```

```
    printf ("Result: %d\n", result);

    return 0;
}
```

A Cilk program can have a C `main` function instead of `cilk_main`, but then the user is responsible for initializing the Cilk runtime system and starting the scheduler. For more information, see section 2.5.3.

2.2.4 Standard Runtime System Options

The Cilk runtime system accepts the following standard options, which must be specified first on a Cilk program's command line:

`-help` List available options.

`-nproc` *n* Use *n* processors in the computation. If *n* is 0, use all processors in the partition. *n* must be at least 0 and no greater than the partition size. The default is 0, using all processors in the partition.

`-serial` Run in serial mode. `cilk_main` is called sequentially, so all spawns in procedures descended from it are likewise turned into sequential calls.

`-print-stats, -no-print-stats, -no-stats` Turn on/off statistics printing at the end of program execution. `print-stats` is the default. The Cilk program must be compiled with statistics enabled for these options to be meaningful.

`-debug` *mode* Enable diagnostic messages to be printed when the Cilk program is compiled with tracing enabled.

`-no-good, -no-provably-good` These options turn off a feature of the work-stealing scheduler which is necessary in theory for guaranteeing efficient time and space bounds, but is sometimes costly in practice.[4]

These options must be specified before all user options, since they are processed by the Cilk runtime system and stripped away before the rest of the user options are passed to `cilk_main`.

For example, one can invoke the `fib_cm5_st` program by

```
cm5> fib_cm5_st -nproc 8 30
```

The runtime system interprets and strips away `-nproc 8`, so that the first and only option seen by `cilk_main` is `30`.

[4]By default, the last returning child of a procedure always migrates its parent to its own processor. This behavior is necessary in theory to guarantee the provably efficient time and space bounds. In practice, however, this extra migration costs some Cilk programs up to 10% of their running time on the CM-5, and even more on SMP implementations of Cilk. The `-no-provably-good` option (or its synonym, `-no-good`) eliminates the extra migration.

2.3 Passing Arrays to Procedures

In a C program, there are two ways of sharing data structures between function invocations: by passing pointers to data allocated on the stack or in the heap, and by using external (global) variables. Neither of these techniques works in Cilk, because of work-stealing. First, pointer arguments that were valid on the processor where a procedure was spawned become meaningless when the procedure is stolen to a different processor. Second, "global" variables in a Cilk program are not actually global. Every processor has a private copy of the program's global variables, making these variables useless for communication and shared storage. The next release of Cilk will remedy these deficiencies with support for distributed shared memory, making pointers and global variables available to Cilk programmers.

This section introduces a Cilk extension that addresses the problem of sharing data structures without resorting to globally coherent shared memory: passing arrays by value. Pass-by-value array arguments turn out to be quite useful, which we illustrate by writing a Cilk program to solve the n-queens puzzle.

Given a (hypothetical) chess board of size `n` by `n`, our problem is to find out the number of ways to place `n` queens on the board such that none of them attack each other (i.e., no two queens are on the same row, column, or diagonal). The Cilk program is shown below.

```
#define MAXQUEENS 20

int safe (int path[], int row, int col);

cilk int search (byvalue int path[MAXQUEENS], int n, int i)
{
    if (i >= n) return 1;
    else
    {
        int ncount[MAXQUEENS];
        int j, sum = 0;

        for (j=0; j<n; j++)
          if (safe (path, i, j)) {
              path[i] = j;
              ncount[j] = spawn search (path[..], n, i+1);
          }
          else ncount[j] = 0;

        sync;
        for (j=0; j<n; j++) sum += ncount[j];
        return sum;
    }
}
```

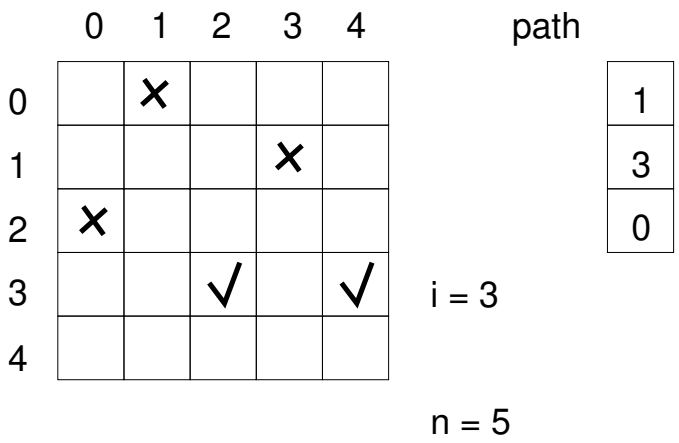


Figure 2.4: Diagram showing one search at row 3. A cross marks the position of a queen already placed, and checks show where recursive searches are spawned. The `path` vector is passed as initial argument to the current search, which records positions of queens that are already placed on the board.

Our solution is organized as a search by the rows on the board. As illustrated in Figure 2.4, the array argument `path` is used to record the positions of queens that have already been committed to rows 0 to `i-1`. These positions are used to enumerate the safe positions for the queen on row `i`, and for each such position, a sub-search is spawned in parallel.

In the argument list of `search`:

```
cilk int search (byvalue int path[MAXQUEENS], int n, int i)
```

the declaration of `path` declares a pass-by-value array argument of size `MAXQUEENS`. The actual array is passed in the spawn statement:

```
ncount[j] = spawn search (path[..], n, i+1);
```

where `path[..]` specifies the array object that is copied into the frame. In Cilk, the expression a`[`$l..u$`]` specifies a section of an array from a`[`l`]` to a`[`u`]`. Since `path` is declared to have fixed size, the two bounds in the section are not specified, and are assumed to be 0 and `MAXQUEENS` $-$ 1.

In this program we would like to save some space by making the size of the `path` vector adjust to the depth of the search. Such a variable sized array argument can be declared by omitting the array size:

```
cilk int search (byvalue int path[], int n, int i)
```

Since the size of the array may now vary from one invocation of the procedure to another, it must be specified when the procedure is spawned. One way to do this would be to use the array section syntax introduced previously, copying the new `path` from the current `path`. Unfortunately, this won't help after we switch to variable-length `path` arrays, since the current `path` only contains `i` elements, and the new path must contain `i+1`. Instead we shall

use an *initialization pointer*, a mechanism that allows the programmer to allocate the array in the frame, then initialize it explicitly:

```
int *new_path;
ncount[j] = spawn search (:new_path[i+1], n, i+1) {
                memcpy ((char*)new_path, (char*)path, i*sizeof(int));
                new_path[i] = j;
            };
```

In the above code, `new_path` is the initialization pointer. The expression `:new_path[i+1]` allocates space for an integer array of size `i+1`, and sets `new_path` to point to the beginning of the array. The spawn statement itself has an optional trailing statement, which here is used to initialize the array. The trailing statement is executed as part of the code to spawn the procedure.

Note that the same technique can be used to have `ncount` allocated in the frame as a variable size array, eliminating the need for the `MAXQUEENS` limit on the size of the board.

2.4 Threads and Explicit Continuation-Passing

To keep its implementation simple, the Cilk runtime system only understands threads and schedules them as the basic units of execution. In this sense, Cilk procedures exist as linguistic abstractions which are translated into threads by the Cilk preprocessor. In order to access the capabilities of the runtime system more directly, the thread abstraction is also supported as a subset of the Cilk language. The following example shows the Fibonacci computation written as two threads:

```
thread fib_T1 (cont int k, int x, int y);  /* forward declaration */

thread fib_T0 (cont int k, int n)
{
    if (n < 2) send_argument (k, n);
    else
    {   cont int k1, k2;

        spawn_next fib_T1 (k, ?k1, ?k2);
        spawn fib_T0 (k1, n-1);
        spawn fib_T0 (k2, n-2);
    }
}

thread fib_T1 (cont int k, int x, int y) {
    send_argument (k, x+y);
}
```

In the thread style, the successor thread in the `fib` procedure is split off as a separate thread `fib_T1`, leaving the initial thread as `fib_T0`.

A thread is spawned by making a *closure*. A closure is a data structure containing a pointer to the thread's code, plus all the arguments needed to execute the thread. In Cilk, the keyword `spawn` is used to create the initial thread of a child procedure, and the keyword `spawn_next` is used to create a successor thread in the current procedure. While child threads are typically created with all arguments available, successor threads usually need to wait for some arguments to arrive in the future. To enable such communication, the sender of the argument must first obtain a reference, called a *continuation*, to the empty slot in the waiting closure. Figure 2.5 shows the closures created after executing `fib_T0` and the continuations passed among child and successor threads. This mechanism, called *explicit continuation-passing*, is used to implement the procedure call/return linkage of Cilk.

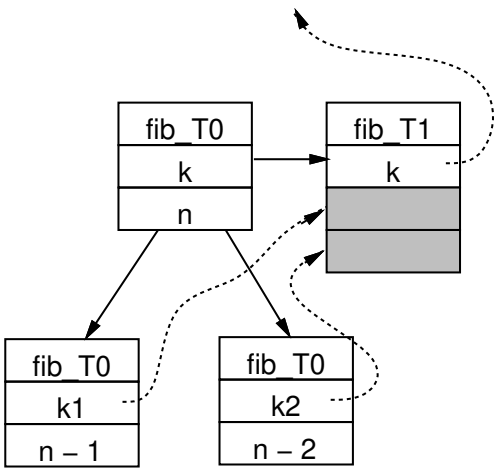


Figure 2.5: Closures created during execution of fib threads

Continuation variables are typed. The type of a continuation is formed from the type of the argument slot to which it points, with the type qualifier `cont` indicating that it is a continuation. In the `fib` example, `k1` and `k2` are declared as continuations pointing to integer arguments:

```
cont int k1, k2;
```

Continuation variables are initialized when the successor thread is spawned. For instance, in the code

```
spawn_next fib_T1 (k, ?k1, ?k2);
```

the form `?k1` specifies an empty argument slot in the closure of `fib_T1`, and stores in `k1` a continuation referring to the slot. A thread that is passed a continuation `k` can send an argument to the waiting closure using the statement

```
send_argument (k, arg);
```

The type of *arg* must be coercible to the base type of the continuation to fit the size and semantics of the slot in the closure.

Threads were the only parallel programming extension supported in release 1.x of Cilk. Release 2.0 introduced procedures, which raise the level of abstraction of Cilk programming. Most Cilk programs can and should be written entirely with procedures. Cilk threads survived in release 2.0 because they reflect directly the scheduling mechanisms implemented in the runtime system, and because certain features needed by Cilk system programming and some user applications only exist in threads. Those features — accumulators, signals, tail calls, and migration threads — are described in the following sections. First, however, we look at how the threads and procedures in your Cilk program can interact and spawn each other.

2.4.1 Spawning Threads from a Procedure, and Vice Versa

All spawns made by a Cilk procedure use *implicit continuation passing*, meaning that instead of specifying a continuation where the result should be sent, the spawn specifies a local variable that should receive the result. As a consequence, when a procedure spawns a thread, it omits the thread's initial argument, the continuation. The continuation is supplied automatically by the Cilk preprocessor, using a reference to the local variable.[5]

For instance, suppose we wanted the `fib` procedure to do half its work using the `fib_T0` thread introduced in the last section. The resulting code is shown below.

```
thread fib_T0 (cont int k, int n);  /* thread declaration */

cilk int fib (int n)
{
    if (n<2) return n;
    else
    {   int x, y;

        x = spawn fib_T0 (n-1);
        y = spawn fib (n-2);

        sync;
        return (x+y);
    }
}
```

The procedure spawns `fib_T0` in precisely the same way as it recursively spawns itself, by assigning the spawn to a local variable. Note that it passes only one argument to `fib_T0`, not two, since the continuation argument is handled implicitly.

[5] Actually, the local variable should be omitted when the spawned procedure or thread returns `void`. Even in this case, however, the Cilk preprocessor supplies an implicit continuation to the spawned procedure or thread.

Now consider the other direction: spawning a procedure from inside a thread. All spawns made by a Cilk thread use *explicit continuation passing*, meaning that a continuation should always be passed as the first argument. For a spawn of a Cilk procedure, this explicit continuation does not correspond to any of the procedure's formal arguments, but the Cilk preprocessor will automatically treat it as the procedure's return continuation. Thus, when the Cilk procedure returns, it will send its return value to the explicitly specified continuation.

Thus, here is a version of `fib_T0` which uses the Cilk procedure `fib` for half of its work:

```
cilk int fib (int n);  /* procedure declaration */

thread fib_T0 (cont int k, int n)
{
    if (n < 2) send_argument (k, n);
    else
    {   cont int k1, k2;

        spawn_next fib_T1 (k, ?k1, ?k2);
        spawn fib (k1, n-1);
        spawn fib_T0 (k2, n-2);
    }
}
```

2.4.2 Accumulators

Accumulators are the first feature we will consider that is supported only by Cilk threads, not by Cilk procedures. Accumulators can be used to gather results from several threads into a single argument slot. To use an argument slot as an accumulator, the following syntax is used to specify the initial value (*init*) and the number of values to be accumulated (n) at thread spawning time:

`spawn_next` *thr* `(...,` `?`*k*`{`*n*`:` *init*`}, ...);`

The continuation thus captured can be used to accumulate values with the statement

`accumulate (`*k, op, val*`);`

where *op* specifies the operation used to accumulate values, which can be one of `add`, `mul`, `and`, `or`, `min`, `max`, or a user defined function (see section 3.7.3). Exactly n values should be sent to activate the waiting thread, but the actual accumulation can happen in any order.

The following shows the Fibonacci example using an accumulator:

```
thread fib_T1 (cont int k, int x);  /* forward declaration */

thread fib_T0 (cont int k, int n)
{
    if (n < 2) accumulate (k, add, n);
    else
```

```
    {   cont int k1;

        spawn_next fib_T1 (k, ?k1{2:0});
        spawn fib_T0 (k1, n-1);
        spawn fib_T0 (k1, n-2);
    }
}

thread fib_T1 (cont int k, int x)
{
  accumulate (k, add, x);
}
```

2.4.3 Signals

Signals are accumulators without any values. The syntax for creating a signal slot is the same as for an accumulator slot except that there is no initial value:

`spawn_next` *thr* `(...,` `?`*k*`{`*n*`}, ...);`

The continuation *k* must have type `cont signal`. Also, in the prototype for *thr*, the argument slot for the signal must be of type `signal`. To send a signal to a continuation, use

`send_argument (`*k*`);`

A signal is useful for indicating that a thread has completed without having to communicate a value. The following shows an example in which we use signals to create a barrier in the code. The thread `spawner` runs several `task` threads and its successor, `barrier`. Each `task` signals the `barrier` thread when it has done its work. The `barrier` thread sends a value to continuation `k` when all of the signals have arrived.

```
thread barrier (cont int k, signal) { send_argument (k, ...); }

thread task (cont signal s)
{
    ... do some work ...
    send_argument (s); /* signal completion */
}

thread spawner (cont int k)
{
    cont signal s;
    int i;

    spawn_next barrier (k, ?s{10});
    for(i = 0; i < 10; i++) spawn task (s);
```

```
}
```

2.4.4 Direct and Tail Calling Threads

Threads can also be called as C functions. Syntactically, this just involves changing the keyword from `spawn` to `call`, as shown in the following example:

```
thread fib_T0 (cont int k, int n)
{
    if (n < 2) accumulate (k, add, n);
    else
    {   cont int k1;

        spawn_next fib_sum (k, ?k1{2:0});
        spawn fib_T0 (k1, n-1);
        call fib_T0 (k1, n-2);
    }
}
```

A direct call of a thread is essentially the tail call optimization frequently used in implementing functional languages. Unlike sequential execution of Cilk procedures, a directly called thread may still spawn threads and leave them to execute in parallel. It is thus strictly an optimization that avoids making a closure and the subsequent scheduling overhead. Since the scheduler needs some work to do after the current thread finishes, direct calling a thread as the last action, whenever possible, generally makes the computation more efficient.

Cilk also provides the keywords `call_next`, `tail_call` and `tail_call_next`, where the `_next` suffix is used for calling successor threads. A tail call can only be issued as the last action in a thread to call the thread itself. It is implemented as a jump to the beginning of the thread after resetting the arguments, thus is even more efficient than `call`, which involves C function call overhead.

2.4.5 Pass-by-value Array Arguments to Cilk Threads

Array arguments as described in section 2.3 can be passed to Cilk procedures and Cilk threads alike. Specific to Cilk threads, however, one can create an array of empty slots in a waiting closure, and send elements of the array individually.

The following example declares an array argument called `result`, which is used to collect data from other threads for the `combine` thread:

```
thread combine (cont int k, byvalue int result[3]);
```

When spawning the `combine` thread, we can use the following syntax to capture a continuation `k1` that refers to the first element in the array. References to other elements in the array are formed by performing arithmetic on the continuation:

```
spawn_next combine (k, ?k1[]);
spawn child1 (k1, ...);
spawn child2 (k1+1, ...);
spawn child3 (k1+2, ...);
```

Continuation arithmetic is analogous to pointer arithmetic, and the same operators are supported. See section 3.7.4 for more details.

2.4.6 Migration Threads

The Cilk runtime system contains a simple storage allocator (see section 2.5.4) which can be used to create data structures shared among threads executing on the same processor. The Cilk language provides a protocol through which the programmer can arrange for the data to be migrated together with the thread.

The protocol only works with Cilk threads, not Cilk procedures, and requires the programmer to define two threads in addition to the main thread. One of these additional threads, called the *migration thread*, is used to pack the data together with the main thread arguments into a new closure to be migrated by the scheduler. The other thread is used to unpack the data from the closure upon reaching the destination.

In the following we shall explain how to use the protocol by writing an abstract search program. For simplicity, assume that the program searches a tree of fixed branching factor `N`, and that the state contained in a tree node is stored in a data structure of type `State`. The goal is to evaluate all the leaves of the tree (assuming results to be non-negative integers), and propagate the maximum leaf value to the root.

```
thread search (cont int k, State *p, int i)
{
    generate_child (p, i);

    if (isleaf (p)) accumulate (k, max, evaluate (p));
    else
    {   cont int k1;
        int j;

        spawn_next sum (k, ?k1{N: 0});
        for (j = 0; j < N, j++) spawn search (k1, p, j);
    }
}
```

Note that one of the arguments to `search`, `p`, is a pointer. Normally this would be bad news for a thread, since `p` is valid only on the processor where the `search` thread was spawned. When the `search` thread is migrated to a different processor, `p` points to garbage — unless the data is also migrated with the thread, which is where the migration thread comes in.

A migration thread is specified by the attribute `migration` and has the same name and prototype as the main thread:

```
migration thread search (cont int k, State *p, int i)
{
    closure *u;

    make_next_closure search_unpack (k, *p, i) {
        u = $;
    }
    return u;
}
```

The mechanism of data migration is shown in Figure 2.6. When the closure of a `search`

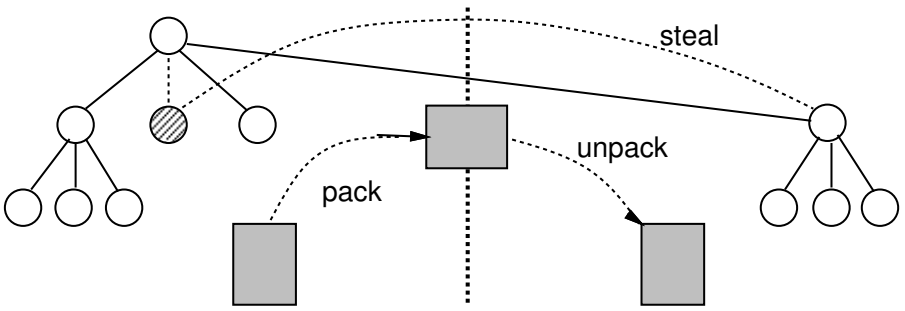


Figure 2.6: Packing and unpacking data during thread migration.

thread is chosen by work-stealing for migration, the runtime system calls the corresponding migration thread, which must pack the data into a new closure and return it immediately to the scheduler. In the migration thread for `search`, the statement

```
make_next_closure search_unpack (k, *p, i) {
    u = $;
}
```

is used to create the new closure. The Cilk keywords `make_closure` and `make_next_closure` are like `spawn` and `spawn_next`, except that the closure created is not posted to the scheduler. Note how the State structure pointed at by `p` is passed by value, so it is copied into the new closure. Within the trailing statement to `make_next_closure`, the special symbol `$` represents a pointer to the newly created closure, which can be captured in a local variable for the migration thread to return to the scheduler.

Note that the new closure is made for a different thread, `search_unpack`. When migrated and scheduled on the destination processor, the unpacking thread must reverse the actions of the migration thread, unpacking the data from the migration closure and calling `search` with a reference to the newly created data. The code for `search_unpack` is shown below:

```
thread search_unpack (cont int k, State s, int i)
{
    State *p = alloc_fstruct_local (sizeof(State));
```

```
    *p = s;
    call_next search (k, p, i);
}
```

2.5 More Advanced Techniques

In the previous sections we have described how to write Cilk programs without having to worry about scheduling. In this section we shall describe some Cilk features that allow the programmer to control some or all of the scheduling decisions.

2.5.1 Overriding Work-Stealing

In combination with the Cilk work-stealing scheduler, it is sometimes useful to force certain threads or procedures to run on specific processors. For instance, if a data structure is statically laid out on your machine, you may want to post a thread to the processor containing the data it needs.

The statement

```
spawn foo (...) @pn;
```

where `foo` can be either a Cilk procedure or thread, posts `foo` on the processor numbered `pn`. The following code is an example of how to use this construct:

```
thread spawner (cont k, int P)
{
    int i;
    for(i = 0; i < P; i++)
    spawn worker (k) @i;
}
```

An explicitly posted thread or procedure becomes local (unstealable) on the destination processor. Thus, the pre-defined variable `Self` (which is always set to the local processor's number)can be used to force a closure to be executed locally.

```
spawn foo (...) @Self;
```

You can also specify in a thread's declaration that it should never be subject to work-stealing. A local thread is specified by the attribute `local`. For example, the thread defined as

```
local thread sum (cont k, int x, int y) { send_argument (k, x+y); }
```

is not subject to migration by work-stealing, i.e., it always executes on the processor where it is spawned.

2.5.2 Handler Threads

A handler thread is specified by the attribute `handler`. Handler threads exist as a low level mechanism to bypass the runtime scheduler. The runtime system keeps a separate queue for these threads, so that they can be executed with high priority, i.e., before any threads in the main ready queue are executed.

In the following example, we illustrate how to use a handler thread to implement what are known as "split-phase" memory fetches. In this situation, the thread that initiates the fetch and the thread that uses the fetched data are separate. Assuming `p` to be a global pointer to an integer, it is shown as the following segment of code:

```
spawn_next use_data (..., ?k1, ...);
spawn fetch (k1, offset(p)) @(pn(p));
```

We define `fetch` to be a handler thread to minimize the latency involved:

```
handler thread fetch (cont int k, int *lp) { send_argument (k, *lp); }
```

Note that a handler thread is not subject to normal scheduling via work-stealing. Unless posted to another processor as in the previous example, it remains a local thread.

2.5.3 Entering the Scheduler from a SPMD Computation

In actual implementations, a Cilk program is first preprocessed to ordinary C code, which executes on all processors in SPMD mode. Multithreaded execution of Cilk procedures and threads only happens within each run of the scheduler. The simplest way to enter the scheduler is to do so automatically via the `cilk_main` procedure, but this technique requires the entire program to be written in mutithreaded style.

To be able to combine the benefit of the SPMD (data-parallel) style of computation with the multithreaded computation supported by the Cilk scheduler, one can explicitly enter the Cilk scheduler from within a data-parallel C program. In this case, the `cilk_main` procedure must not be defined. Instead, the following runtime system interface must be used:

```
int Self;
int cilk_active_size;
int cilk_mode;

void CilkInit (int *pargc, char **argv);
void CilkExit (int exit-code);

[result =] schedule proc (arg_1, ...);
```

The following shows an example of typical use:

```
int main (int argc, char *argv[])
{
    int n, result;
```

```
    CilkInit (&argc, argv);

    n = atoi (argv[1]);
    result = schedule fib (n);
    printf ("result: %d\n", result);

    CilkExit (0);
}
```

Before entering the scheduler, its state must be initialized by calling

```
CilkInit (&argc, argv);
```

where `argc` and `argv` are arguments supplied to the C `main` function. Since `CilkInit` processes the standard Cilk runtime system options, this must happen before any of the user options are processed. The function `CilkExit` should be used to clean up the scheduler state and terminate the program.

After initialization, the Cilk scheduler is entered via the construct

```
result = schedule fib (n);
```

The `schedule` statement is in fact part of the Cilk language, whose effect is to enter the scheduler to run `fib (n)` as the first procedure. `schedule` can only be used for this purpose. However, it may be used multiple times within the main control of the SPMD C program.

The global variable `Self` is always set to the processor number, which should not be altered. `cilk_active_size` can be set and reset before entering the scheduler to change the number of processors to participate in the computation. `cilk_mode` can be set before entering the scheduler to control the scheduler modes and is something not available when using `cilk_main`. The following modes are supported:

`CILK_AUTO`, `CILK_AUTO_KEEP`, `CILK_MANUAL`, `CILK_MANUAL_KEEP`,

In the `CILK_AUTO` mode, the Cilk runtime system uses work stealing, which is also the default mode. In the `CILK_MANUAL` mode, work stealing is turned off. In either mode the data heap is reset when the scheduler exits. If one wishes to keep the data structures allocated in the heap, which may be accessible either through the result pointer or some global variable set during computation, then `CILK_AUTO_KEEP` or `CILK_MANUAL_KEEP` should be used.

2.5.4 Data Structure Primitives

The Cilk runtime system provides a simple storage allocator for local data objects which can be used to creat per-processor global data structures together with migration handlers, or distributed global data structures by creating global references to these objects. The primitives

```
void *alloc_fstruct_local (int size);
void free_fstruct_local (void *block);
```

allocate and free blocks of memory, where *size* is in units of words. The storage allocated is

taken from the Cilk runtime heap, which is reset after each run of the scheduler by default. Therefore if one wishes to keep them over to the next run of the scheduler, before the current run the `cilk_mode` variable must be set to either `CILK_AUTO_KEEP` or `CILK_MANUAL_KEEP`.

2.5.5 Manual Scheduling in Cilk

In conjunction with the `CILK_MANUAL` mode, which turns off work-stealing, the `@dest` annotation can be used to schedule a computation by explicitly posting all threads. To illustrate, we shall consider a simple shared memory program using the Cilk storage allocator.

The shared memory abstraction we consider here is very primitive. It supports locally allocated data objects and global pointers. A global pointer (type `globptr`) is made of two components: a processor number (`pn`) and a local pointer (`offset`), which can be manipulated via the following interface:

```
globptr make_globptr (void *lp);
int pn (globptr p);
void *offset (globptr p);
```

(Note that `globptr` is not part of the Cilk language. One way to implement it uses a structure containing a processor number and a local pointer.)

Our example program makes a full binary tree and then traverses the tree to count the number of leaves. The data structure representing a node of the tree is defined as follows:

```
typedef struct {
    globptr left;
    globptr right;
} node;
```

The following code shows the Cilk procedure that makes the binary tree. It calls itself recursively to make two subtrees of height `h` $-$ 1, then allocates a node above them to form a tree of height `h`. Note that we do not specify where each invocation of `make_tree` should be executed. We rely on work-stealing to distribute the allocation of the tree nodes across the processors.

```
cilk globptr make_tree (int h)
{
    if (h==0) return 0;  /* null pointer indicates leaf */
    else
    {
        globptr left, right;
        node *np;

        left = spawn make_tree(h-1);
        right = spawn make_tree(h-1);

        sync;
```

```
        np = (node *) alloc_fstruct_local (2);
        np->left = left;
        np->right = right;
        return make_globptr (np);
    }
}
```

Now for the `count_leaves` procedure. Unlike `make_tree`, we must explicitly post the `count_leaves` procedures to follow the global pointers:

```
cilk int count_leaves (globptr p)
{
    if (p == 0) return 1;
    else
    {   node *tree = (node *) offset (p);
        globptr left = tree->left, right = tree->right;
        int x, y;

        x = spawn count_leaves (left) @(pn(left));
        y = spawn count_leaves (right) @(pn(right));

        sync;
        return x+y;
    }
}
```

The following code is the top level control of the program. The scheduler is entered twice: the first time to run `make_tree`, the second time to run `count_leaves`. This is done so that we can switch the scheduler mode to `MANUAL`, which turns off work-stealing:

```
int main (int argc, char *argv[])
{
    int h, result;
    node *tree;

    CilkInit (&argc, argv);
    h = atoi (argv[1]);

    cilk_mode = AUTO_KEEP;
    tree = schedule make_tree (h);

    cilk_mode = MANUAL;
    result = schedule count_leaves (tree);

    CilkExit (0);
}
```

The mode `AUTO_KEEP` indicates to the scheduler to return the data structures allocated via `alloc_fstruct_local` for the next run of the scheduler (see section 2.5.3).

Chapter 3

Language Reference

3.1 Basic Concepts

In Cilk, the basic unit of scheduling and execution is a *thread*. Threads are grouped together to form *procedures*, which are the parallel equivalent of C functions. Procedures can be directly defined in Cilk, whithin such a procedure threads are punctuated by synchronization points. Threads can also be directly defined in Cilk, in which case the notion of a procedure is maintained through a system of annotations in the Cilk language.

To avoid confusion of terminology, we shall use the terms "Cilk thread" and "Cilk procedure" to refer to the directly defined threads and procedures, and use the terms "thread" and "procedure" in a more abstract sense. At runtime, procedure and thread spawning forms a dynamic tree, with data dependencies among threads forming a dag (see section 1.3).

While Cilk procedures form an abstraction that most C programmers will feel comfortable with, Cilk threads provide an abstraction that is more primitive but necessary for direct access of some runtime mechanisms.

3.1.1 Closures and Continuations

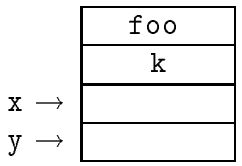
A Cilk thread is spawned by making a closure. A closure is a data structure that captures all information needed to execute the thread, containing the thread pointer and all arguments passed to the thread. To enable thread communication and synchronization, a closure can be created waiting for some arguments to arrive in the future, thus it may contain empty argument slots. A closure is said to be *full* if it has all of its arguments, otherwise it is *waiting*.

A *continuation* is a global reference to an empty argument slot, to which an argument can be sent. For example, the statement

```
spawn foo (k, ?x, ?y);
```

creates a closure for `foo`, and initializes `x` and `y` as continuations pointing to the two empty slots:

[1]This chapter was written by Yuli Zhou and Rob Miller.



Usually, both `x` and `y` will be passed to new threads which will eventually send arguments via

```
send_argument (x, arg);
```

that fills the slot referenced by `x`. The closure will be *posted* to the scheduler when it becomes full, which will later schedule it for execution.

3.1.2 Frames

When a Cilk procedure is spawned, an activation *frame* for the procedure is made and given to the scheduler. A frame is a closure shared by the initial and successor threads in the same procedure, thus from a runtime system point of view, frames are just extended closures. In this document, we shall often use the term "closure" to also refer to frames for procedures. The Cilk preprocessor breaks down Cilk procedures into threads. At runtime, the thread pointer in the frame is initialized to the first thread in the procedure, then mutated to the successor threads as computation unfolds.

The continuation-passing linkage of procedures is handled by the Cilk preprocessor and hidden from the programmer. Specifically, when spawning a procedure, the return continuation (refering to the return slot in the parent frame) is passed as an implicit first argument. Within the procedure, the statement

```
return val;
```

is used to send the return value using the implicit return continuation, which also has the effect of terminating the current procedure execution.

3.1.3 Runtime Scheduling and Work Stealing

As we mentioned in section 1.3, the Cilk runtime system is designed to run multiple serial computations, one on each processor, in order to maintain the space bound of the equivalent of one execution stack per processor. In the meantime, it uses work-stealing to migrate computations on demand in order to balance the load among the processors.

At runtime, the Cilk scheduler manages one ready queue per processor that keeps closures by their spawning depth. Closures for successor threads are posted at the same level, while those for child threads are always posted to the next level. For local execution, the scheduler always takes the most recently spawned closure at the deepest level, according to the serial order of execution. The mechanism of work-stealing is implemented so that as soon as a processor's ready queue becomes empty, the processor attempts to steal a closure from a randomly chosen "victim." The closure chosen for the steal is the most recently spawned closure in the shallowest level of the victim's ready queue. Intuitively, a thread in the

shallowest level is likely to contain more work, so the thief processor will have more work to do before it must steal again.

3.2 Program Structure

A Cilk program consists of ordinary ANSI C code plus definitions and declarations of procedures and threads. Usually, there will be one procedure named `cilk_main` in the program, which takes the standard C command line arguments and returns an integer, just like the C `main` function. At runtime, `cilk_main` will be the initial procedure invoked from the runtime system, from which all computation ensues.

Within a Cilk program, C code and C functions are used for sequential computation. C functions can be called from Cilk procedures and threads, but Cilk procedures and threads cannot be invoked from C functions. The only exception to this rule is a sequential `call` to a Cilk procedure, which treats the procedure exactly like a C function (i.e., it does not run in parallel, and all of its computation is sequential).

3.3 Keywords

The following words have special meaning in Cilk, and thus cannot be used as ordinary identifiers in Cilk code:

```
accumulate, byvalue, call, call_next, cilk, cilk_main, closure, cont,
handler, local, make_closure, make_next_closure, migration,
schedule, send_argument, signal, spawn, spawn_next, sync,
tail_call, tail_call_next, thread
```

Ordinary C code is permitted to use Cilk keywords as identifiers if one of the following conditions is true:

- the C code appears in a file with extension `.c` or `.h` (the conventional extensions for C source). The Cilk preprocessor treats files with these extensions as straight C. Thus, standard header files included by a Cilk program may use Cilk reserved words as identifiers.

- the C code is preceded by `#pragma lang +C` and followed by `#pragma lang -C`. These directives tell the Cilk preprocessor to treat the code between them as straight C. This mechanism should be used when the C code is found within a Cilk program (`.cilk`) file.

For instance, the following C code uses `thread` as a variable name. It is bracketed by `#pragma lang` directives to prevent the preprocessor from issuing syntax errors.

```
#pragma lang +C
int thread;
thread = thread+1;
#pragma lang -C
```

3.4 Types

The thread abstraction in Cilk introduces the following new types: `cont`, `closure` and `signal`. With the exception of `signal`, which has special restrictions, these types may appear anywhere in a Cilk program, including ordinary C functions and declarations.

`cont` is a type qualifier used to declare continuations. Continuation declarations have the general form

`cont` *type var*

where `type` is called its *base type*. A continuations is a reference to a closure slot having the based type, thus its usage is similar to the C "`*`" (pointer-to) type qualifier. Continuations are captured at thread spawning time (section 3.7.2), and subsequently passed to other threads to enable values to be sent to the referenced slot (section 3.7.3).

`signal` is a special type, which is introduced for the frequent cases where a thread only needs to receive a notification from another thread which carries no value. Technically, `signal` specifies a 0-sized slot in the closure, thus continuations can be defined to refer to a signal slot (section 3.7.2). Since the signal carries no value, only the continuation is significant: the signal itself can never be used. A signal only serves as a place holder in the thread argument declaration list for the purpose of type-checking.

3.5 Procedure/Thread Definitions and Declarations

Cilk extends ANSI C with constructs to define procedures and threads:

procedure: `cilk` *type proc* `(`*arg-decl*$_1$, ..., *arg-decl*$_n$`)` *body*
thread: [*attrib*] `thread` *thr* `(cont` *type k, arg-decl*$_1$, ..., *arg-decl*$_n$`)` *body*

The keyword `cilk` specifies a procedure definition, and the keyword `thread` specifies a thread definition. Argument declarations follow the ANSI C convention. When the body of the definition is the null statement (`;`), both forms are taken to be prototype declarations.

Note that procedures have a return type, but threads have an explicit continuation argument (appearing first) whose base type is the return type of the thread. An empty or `void` argument list specifies a procedure or thread with no argument.

The optional *attrib* field to a thread definition can be one of

`local`, `handler`, `migration`

The use of these keywords will be described later in section 3.10 and 3.11.

Procedure and thread bodies take the form of a C compound statement:

{ *decl*$_1$ ... *stmt*$_1$ ... }

Here the declarations follow the ANSI C convention. All ANSI C statement and expression syntax are allowed in the procedure or thread body, with the following exception: *New types may not be defined in a procedure body.* Thus, all `struct`, `union`, and `enum` definitions and `typedef` declarations used in a Cilk program should appear outside of procedure bodies.

Procedure and thread bodies may also contain Cilk statements, including procedure and thread spawns, synchronization, and communication.

3.6 Spawning

The following Cilk statement forms can be used to spawn Cilk procedures or threads to start parallel computations:

stmt: [*var* `=`] `spawn` *proc_or_thread* `(` arg_1, ..., arg_n `)` [`@(`*expr*`)`] *stmt*
`spawn`[`_next`] *proc_or_thread* `(` *k*, arg_1, ..., arg_n `)` [`@(`*expr*`)`] *stmt*

The first form, the implicit continuation-passing form, is used to spawn procedures or threads from a Cilk procedure. The left-hand side *var* `=` must be present if and only if *proc_or_thread* has a non-void return type. *var* must be a local variable, or an element of a locally declared union, structure or array. When *proc_or_thread* is a procedure, *var* must have the same type as the return type of the procedure. When *proc_or_thread* is a thread, *var* must have the same type as the base type of thread's initial continuation argument.

The second form, the explicit continuation-passing form, is used to spawn procedures or threads from a Cilk thread. The keyword `spawn` should be used to create a child thread that starts a new procedure invocation, whereas `spawn_next` should be used to create a successor thread within the same logical procedure. When *proc_or_thread* is a procedure, the continuation argument *k* must have the same base type as the return type of the procedure. When *proc_or_thread* is a thread, *k* must have the same continuation type as the thread's initial continuation argument.

In either form, *proc_or_thread* must be defined or declared as a Cilk procedure or thread with the correct number and types of arguments for arg_1, ..., arg_n.

Spawning a Cilk procedure or thread creates a closure. If the optional `@(`*expr*`)` is present, the closure will be posted to the processor number *expr*, otherwise it will be posted locally. If all arguments are available then posting happens immediately.

The trailing *stmt* can be null (`;`) or any Cilk statement. Since it is executed before the closure is posted, the trailing statement is handy for initializing the closure. See section 3.7.1 for more details.

A procedure or thread may be spawned even if it is defined in a different source file, as long as a prototype for it is in scope.

3.7 Passing Arguments and Returning Values

Arguments passed to spawned procedures or threads can be any valid C expression. In addition, Cilk provides extensions to pass arrays by value (section 3.7.1) and to capture continuations referring to slots in waiting closures (section 3.7.2).

Within a Cilk procedure, the statement

`return` *expr*`;`

can be used to communicate a return value to the spawning procedure, with the additional

effect of terminating the execution of the current procedure.

Within a Cilk thread, the `return` statement merely terminates the thread's execution, without sending a value. Threads must communicate via explicit continuation-passing, using an assortment of primitives provided in the Cilk language (section 3.7.3).

3.7.1 Passing Array Arguments by Value

Cilk introduces the storage class `byvalue`, specified before an array argument declaration, to indicates that the array should be copied when it is passed. For example:

```
procedure queens (byvalue int path[], int i, int n) ...
```

Two kinds of pass-by-value array arguments can be declared:

arg-decl:	`byvalue` *var*`[`*expr*`]`	fixed-size array
	`byvalue` *var*`[]`	variable-size array

The actual size of a variable-size array argument is specified at thread spawning time. Variable-size array arguments can occur anywhere inside the argument list.

When spawning a procedure or a thread, there are two ways to supply actual arguments declared to have `byvalue` array type: with a *range expression* or with an *initialization pointer*.

A range expression passes a specified range of an existing array. It takes one of the following forms:

arg:	*expr*`[..]`
	expr`[`$expr_l$`..`$expr_u$`]`

The first form can only be passed to an argument declared to have `byvalue` array type of fixed-size, where the size of the array is taken from the declaration. The second form can only be passed to an argument having `byvalue` variable-size array type. The array segment passed includes elements at both the lower and upper bounds (i.e., the size of the array object is calculated as $expr_u - expr_l + 1$).

An initialization pointer takes one of the following forms

arg:	:*var*`[]`
	:*var*`[`*expr*`]`

The arguments corresponding to these forms must have `byvalue` array types of fixed and variable size, respectively. The size of the array is taken from the declaration in the first form, and is specified by *expr* in the second form. Either form has the effect of allocating an array of the specified size in the closure, and sets *var* to be a pointer to the beginning of the array.

The array allocated by an initialization pointer must be initialized explicitly in the spawn's trailing statement (see section 3.6). *var* is set to point to the first element of the array in the closure, and must be declared to match the array element type. Example:

```
int *new_path;
ncount = spawn queens (:new_path[i+1], i+1, n) {
```

```
        memcpy ((char*)new_path, (char*)path, i*sizeof(int));
        new_path[i] = j;
    }
```

Since the closure is automatically posted to the scheduler after executing the trailing statement, the initialization pointer should not be referenced after the spawn statement.

3.7.2 Continuation Capturing Arguments

For Cilk threads that are spawned with waiting closures, the following forms can be used to capture continuations referring to the empty argument slots:

arg : `?`*var*
`?`*var*`{`*expr*$_j$`:` *expr*$_i$ `}`
`?`*var*`{`*expr*$_j$ `}`
`?`*var*`[]` | `?`*var*`[`*expr*`]`

An argument of one of the following forms

`?`*var*
`?`*var*`{`*expr*$_j$`:` *expr*$_i$`}`
`?`*var*`{`*expr*$_j$ `}`

allocates an empty slot in the closure, and initializes *var* to a continuation referring to that slot. In all of the forms *var* must be declared to have the type `cont` *type*, where *type* is the type of the argument slot to which it points.

The argument forms here differ in how many argument values are expected and how the values are deposited in the empty slot. Specifically:

- `?`*var* allocates a simple slot that waits for exactly one argument to be sent.
- `?`*var*`{`*expr*$_j$`:` *expr*$_i$`}` allocates an *accumulator* slot, expecting *expr*$_j$ values and initializes the slot to *expr*$_i$. The closure is not considered full until all *expr*$_j$ values arrive. The means of accumulation of these values is unspecified; it depends on which primitives are used to send the arguments (see section 3.7.3).
- `?`*var*`{`*expr*$_j$ `}` specifies a *signal* slot. The argument must be declared to have the type `signal`, and the slot has size 0 (in effect, no slot will be allocated in the closure for a signal). As in the previous case, the closure will be waiting for an additional *expr*$_j$ signals.

Both of the following argument forms

`?`*var*`[]`
`?`*var*`[`*expr*`]`

allocate an array of simple slots and initialize *var* to a continuation pointing to the beginning of the array. The first argument form must have `byvalue` fixed-size array type, and the size is taken from the type declaration. The second form must have `byvalue` variable-size array type. Continuation arithmetic can be used on *var* to derive continuations that reference other slots in the array (see section 3.7.4).

3.7.3 Thread Communication Primitives

Cilk threads communicate via explicit continuations using the following statements:

```
send_argument (k, v);
accumulate (k, op, v);
send_argument (k);
```

Here v is first coerced to the base type of the continuation k as if for assignment.

The first form is used to send an argument to a simple slot in a waiting closure. The third form is used to send a signal. The second form takes an additional *op* argument, which is used to send an argument to an accumulator slot, where *op* is an operator that specifies the accumulating operation.

There are six predefined accumulation operators:

```
add, sub, and, or, min, max
```

In addition to these predefined operators, a user-written C function may act as an accumulation operator. Such a function *op* must have type `void (`T `*, `T `*)`, where T is the base type of the continuation. The first argument is a pointer to the value being accumulated; the second argument is a pointer to the accumulator slot. For example, a user-defined integer add operator might look like:

```
void int_add (int *v, int *a) { *a += *v; }
```

User defined operators should be commutative and associative, since the order in which accumulations will occur is undefined.

3.7.4 Continuation Arithmetic

With thread creation, for example

```
cont int x;
spawn_next foo (1, ?x[SIZE]);
```

it is only possible to capture a single continuation `x` pointing to the first element of the array. In order to send the other elements of an array argument, it is necessary to index the continuation as you would index a C pointer:

```
send_argument(k + i, v );
```

In general, k `+` i returns a new continuation pointing to the ith element counting from the reference point of k, where the size of each element is the size of k's base type.

It is illegal to index a continuation that points to a closure on a remote processor.[2] In practice, a thread should only index continuations that it created, not continuations that were passed in by its parent. For example, the continuation arithmetic below is safe:

[2]This is a consequence of the current implementation of the Cilk runtime system, which creates a stub of the return argument slot when it steals a computation. It is anticipated that continuation arithmetic will eventually be replaced by pointer arithmetic in a shared global address space.

```
thread parent(cont int k, ...)
{
    cont int x;

    spawn_next parent2(k, ?x[3], ...);
    spawn child(x, ...);
    spawn child(x+1, ...);
    spawn child(x+2, ...);
}
```

but `child` may not change the continuation it receives from `parent`.

Continuation arithmetic may be performed with all the usual C operators for pointer arithmetic: `+`, `-`, `++`, `--`, `+=`, `-=`. Unlike pointers, however, continuations may not be subtracted to find their relative displacement.

3.8 Synchronization

Within the body of a Cilk procedure, the statement

```
sync;
```

can be used to wait for all child procedures spawned before it in the current procedure to return. Typically, it is used to block the execution of the current procedure until all return values are available:

```
x = spawn foo (...);
y = spawn bar (...);
...
sync;
/* values of x, y available */
```

When the procedure resumes, execution starts at the point immediately after the sync statement.

Cilk threads are non-blocking, and thus cannot contain sync statements. Synchronization happens implicitly as the side-effect of sending arguments to threads, in the sense that a thread waits for all arguments to arrive before it is ready for execution.

3.9 Sequential Execution

In Cilk, both procedures and threads can be directly called as C functions. However, calling procedures is quite different from calling threads, as further described below.

3.9.1 Sequential Execution of Procedures

The following expression calls a Cilk procedure sequentially:

`call` *proc* `(` arg_1, ...`)`

The type of the expression is the return type of the Cilk procedure.

If a Cilk procedure is invoked in this way, all computation specified by the procedure, including child procedures that it spawns, are executed sequentially on the local C stack, i.e., exactly like C functions. This mechanism is useful for increasing the granularity of threads, thus reducing the scheduling overhead, at the potential cost of reduced parallelism.

3.9.2 Direct and Tail Calling Threads

The following statement forms can be used to call threads:

`call[_next]` *thr* `(` *k, arg*$_1$, ... `);`
`tail_call[_next]` *thr* `(` *k, arg*$_1$, ... `);`

`call` invokes the thread *thr* exactly as a C function. `tail_call` is more efficient, but is restricted in that *thr* must be the very thread in whose body it appears[3]. Both the direct and tail calls avoid making a closure and completely bypass the scheduler. The `_next` suffix has the same effect of specifying a successor thread as does `spawn_next`. Unlike calling Cilk procedures, a direct or tail called thread may still spawn threads that can execute in parallel.

3.9.3 Notes on Argument Passing

When calling Cilk procedures or threads as C functions, arguments passed to them must be C expressions as no closures are created. Specifically, no continuation-capturing arguments can be specified when calling a thread. In addition, a `byvalue` array argument must be passed by reference. For the latter, the Cilk preprocessor generates C code that is consistent with this interpretation of array arguments, i.e., if we have a procedure declared as

```
cilk int foo (byvalue int a[10]) { ... }
```

and `b[10]` is an array, then `b[10]` will be copied into the frame when `foo` is spawned, but only the pointer `b` will be passed to `foo` when it is called.

If an argument is a structure, then it is passed by value no matter whether the procedure is spawned or called. When a structure is large, one may wish to avoid the extra copying during direct calls. This can be achieved by specifying it as an array argument of 1 element. For example, instead of defining

```
cilk int foo (struct bar x) { ... }
```

and having to pass its `struct` argument by value when `foo` is called, change the definition to

```
cilk int foo (byvalue struct bar xp[1]) { ... }
```

[3]A tail call is implemented as a jump back to the entry of the thread after resetting the arguments.

3.10 Annotations for Thread Scheduling

Under the default Cilk scheduling policy, the programmer specifies neither where nor exactly when a thread will be executed: it is up to the scheduler to execute the threads as they become ready or migrate them upon work stealing requests.

The different versions of `spawn` and `spawn_next` should be regarded as annotations providing hint to the scheduler so that it can group together threads logically belonging to the same procedure invocation for scheduling purposes (see section 3.1.3).

For more complicated situations, Cilk provides a more elaborate system of annotations by which the programmer can post threads to specific processors, to make some threads not stealable, or to execute certain threads at an higher priority.

The form

`local thread` *thr* `(`*arg-decl*$_1$`, ...)` *body*

defines a thread that stays local, i.e., it will not be migrated by work stealing. The statement

`spawn[_next]` *thr* `(`*arg*$_1$`, ...) @(`*expr*`)` *stmt*

creates a closure which will be posted to the processor numbered *expr*. Upon arrival it becomes a local closure on the destination processor. Consequently, the closure created by

```
spawn foo (...) @(Self)
```

will not be stolen (`Self` is a global variable defined in the runtime system, whose value is the local processor's number).

The form

`handler thread` *thr* `(`*arg-decl*$_1$`, ...)` *body*

defines a handler thread. A handler thread is similar in every respect to an ordinary thread except that it has higher scheduling priority, i.e., once ready it is scheduled to execute before all the ordinary ready threads.

A handler thread is not subject to migration under work stealing. Unless the `@(`*proc*`)` annotation is specified, a handler thread becomes a local thread upon creation.

3.11 Migration Threads

Cilk provides a mechanism by which threads may be migrated together with their local data structures during work-stealing. Currently it is implemented as a user level protocol that requires the programmer to specify three threads: the ordinary thread, an additional *migration* (packing) thread, and an unpacking thread.

First, the following statement forms are equivalent to `spawn`/`spawn_next` except the closure created will not be automatically posted even if it is created full:

`make[_next]_closure` *thr* `(`*arg*$_1$`, ...)` *stmt*

Here again, `make_next_closure` is for creating a successor thread, and `make_closure` is for creating a child thread.

The migration thread has the special syntax

`migration thread` *thr* `(`*arg-decl*$_1$`, ...)` *body*

Here *thr* must already be defined as a ordinary thread with the same argument prototype. The idea is that at migration time, this thread will be invoked to pack a new closure that is migrated instead. We first explain the protocol using the following example.

Suppose that the thread `foo` will be passed a reference to a locally allocated data structure of some type `typ` (object of type `typ` may further contain pointers, for example to form a linked list):

```
thread foo (cont int k, typ *p) { ... }
```

As a result, `foo` cannot be migrated since `p` will point to garbage on another processor.

The solution is for the user to specify a migration thread to pack the data structure into a new closure, which is migrated instead of the original closure, and to specify an unpack thread which will be used to create a local copy of the data structure once the new closure has reached its destination:

```
migration thread foo (cont int k, typ *p)
{
    closure *cp;
    char *a;

    make_next_closure foo_unpack (k, :a[get_size(p)]) {
        copy_into (a, p);
        cp = $;
    }
    return (cp);
}
```

The way the data structure is copied completely depends on the user supplied function `copy_into`, which for example can flatten a linked list into array `a`.

The new closure must be returned to the scheduler, which posts it to the destination processor instead of the original closure for `foo`. In the trailing statement, the special symbol `$` is bound to a pointer to the newly created closure for this purpose.

In the migration thread, the new closure is made for the thread `foo_unpack`, which must do the reverse of the migration thread:

```
thread foo_unpack (cont int k, char a[..])
{
    typ *p = reconstruct_from (a);
    call_next foo (k, p);
}
```

The unpacking thread uses the user supplied function `reconstruct_from` to make a local copy of the original data structure, then directly calls `foo`.

In order for things to work out correctly, the migration thread must be prototyped along with the original thread and the unpacking thread, and it must have the same argument list as the original thread. The unpacking thread, however, is not related to the original thread, and it is the programmer's responsibility to provide the unpacking thread with the desired behavior. As a final note, both the migration thread and the unpacking thread should use the `_next` variants of the required primitives so that the resulting thread will execute at the same level as the original thread would have executed.

Appendix A

Copyright and Disclaimers

Permission to use, copy and modify this program for research purposes without fee is hereby granted, provided that this copyright and permission notice appear on all copies and supporting documentation, and the name of M.I.T. not be used in advertising or publicity pertaining to distribution of the program without specific prior permission. M.I.T. makes no representations about the suitability of this software for any purpose. It is provided "as is" without express or implied warranty.

Appendix B

Installation Instructions

Currently, these installation procedures only apply to the CM5. Hopefully, they will not need much modification for installing on other systems.

B.1 Finding Cilk at MIT

This section explains how to use Cilk 2.0 at MIT. If you are not at MIT, refer to the next section for instructions on obtaining Cilk by ftp.

An installed copy of Cilk can be found in `/a/randall/Cilk2.0/` on `scout.lcs.mit.edu`. There is an example `Makefile` in `/a/randall/Cilk2.0/examples/` that you can use to build your own Cilk programs.

B.2 How to Obtain Cilk

Cilk can be obtained by `ftp`ing the file `Cilk2.0.tar.Z` from

`theory.lcs.mit.edu:/pub/ftp/pub/cilk/Cilk2.0.tar.Z`

Cilk should be installed on the compile-server for the CM5.

B.3 How to Install Cilk

After copying `Cilk2.0.tar.Z` into a directory on your system, do the following things:

- type '`uncompress Cilk2.0.tar.Z`'. This will create a file named `Cilk2.0.tar`.
- type '`tar -xf Cilk2.0.tar`'. This will create a directory named `Cilk2.0/` and put all of the Cilk software into this directory. You may want to remove the `Cilk2.0.tar` file after this is done.
- type '`cd Cilk2.0`' followed by '`more README`'. This file will list the installation instructions for Cilk 2.0. Follow the instructions to install Cilk, including the communication library (strata), the preprocessor (cilk2c), and the run-time system. The `Readme` file

also includes instructions on running some test programs and on building the reference manual.

B.4 How to run the regression tests

B.4.1 Strata regression test

Move to the `Cilk2.0/strata` directory and type '`jrun do-test`'. This should run the strata regression test and tell you something about the raw performance of the CM5 you are using.

B.4.2 Cilk run-time system regression test

Move to the `Cilk2.0/rts` directory and type '`make testall_cm5`' to build the regression test program (this may take several minutes). Then type '`jrun testall.job`' to run the regression test. The regression test program will print '`OK : ...`' for correctly functioning primitives and print '`BAD: ...`' for malfunctioning primitives. It may also hang if a primitive is seriously broken. The program may also print '`???: ...`' if it is unable to determine whether a particular primitive is working or not.

B.4.3 Running the Cilk examples

Move to the `Cilk2.0/examples` directory and type '`make fib_cm5_st`'. This will make an executable for `fib` for the CM5 with statistics gathering enabled. Then, type '`jrun fib.job`' to run the fib example. For the other examples (`queens`, `tree`, `adq`), simply repeat the above procedure with their name replacing `fib`.

B.5 Mailing Lists

If you use Cilk, you may wish to be on the cilk-users mailing list. To join the cilk-users mailing list, send mail to

`cilk-users-request@theory.lcs.mit.edu`

To send mail directly to the cilk-users mailing list, use

`cilk-users@theory.lcs.mit.edu`

B.6 Reporting Bugs

Please report bugs in the Cilk system by electronic mail (email) to

`bug-cilk@theory.lcs.mit.edu`

Appendix C

The Cilk Preprocessor

NAME

cilk2c — The Cilk language preprocessor

SYNOPSIS

cilk2c [*options*] [*infile.cilk*]

DESCRIPTION

cilk2c is the preprocessor for the Cilk language as defined in the *Cilk Language Reference Manual*. It reads from an input Cilk program file, which by convention has the extension *.cilk*, and generates ordinary C code in the output file, which has the same root name as the input file but the extension *.c*. (If the input filename is omitted, *cilk2c* reads from standard input and writes to standard output.) To produce an executable, the generated C file must be compiled using *gcc* and linked with the Cilk runtime library.

Unlike previous versions of the preprocessor, *cilk2c* includes full syntax checking and type checking for Cilk. If your Cilk program contains errors, *cilk2c* will print error messages to standard error, and no C output will be produced.

The following options are available. Multiple options must be specified separately; they cannot be stacked.

General options

-help Print a help message.

-options Print all options.

-copy Print copyright information.

-v Print version information.

Output options

-link [*other_files ...*] Emit signature table for *infile.cilk* and *other_files*

-o ⟨**name**⟩ Write C output to ⟨name⟩

[1]This man page was written by Rob Miller.

-N Omit #line, format for readability

Warning options

-ansi Disable GCC extensions and undefine `__GNUC__`

-W*n* Set warning level; *n* in 1-5. Default warning level is 4.

-Wall Same as -W5.

-il Ignore line directives (use actual line numbers).

-offset Print offset within the line in warnings/errors.

-name *x* Use stdin with *x* as filename in messages.

Macro preprocessor options

-P*str* Set the preprocessor command to *str*.

-pre Print the preprocessor command and flags.

-I*path* Specify path to search for include files.

-D*macro*[=*Value*] Define *macro* (with optional value).

-U*macro* Undefine *macro*.

-H Print the name of each header file used.

-undef Do not predefine nonstandard macros.

-nostdinc Do not scan standard include files.

Debugging options

-lex Show lexical tokens.

-yydebug Track parser stack and actions.

-insert Track symbol creation.

-sym Print out symbol tables after parse.

-ast Print out syntax tree (after last phase).

-nopre Don't preprocess.

-nosem Don't semantic-check.

-notrans Don't transform syntax tree.

-noprint Don't write C output.

CC compatibility options

-- Toggles ignoring of unknown options. Designed for makefile compatibility with your C compiler. For instance, in your makefile you can pass any compiler flags to *cilk2c* by bracketing them with **--**: for instance,

```
cilk2c -- $(CFLAGS) --
```

cilk2c will use any options that it recognizes, such as -I and -D, and ignore the rest.

BUGS

gcc is required to compile the C code generated by *cilk2c*, as it uses some *gcc* extensions.

There are some known bugs in *cilk2c*'s ANSI C type-checking. The type equivalence test fails to work on array types whose dimensions are not literal constants, so the type-checker fails to report the type disagreement in:

```
extern int a[1+1];
int a[0+1];
```

cilk2c cannot detect pointer arithmetic which is non-constant at load time. For example, it allows the following initialization of the global variable `diff`, which is technically illegal in ANSI C (and rejected by gcc):

```
int i;
int j;
int diff = &j - &i;
```

Finally, *cilk2c* fails to detect multiple definitions (i.e., initializations) of an external identifier. For example, C-to-C accepts the following top-level definitions without complaint:

```
int x = 5;
int x = 6;
```

Appendix D

Specification of the Cilk Runtime System

D.1 Errata

Currently this document does not uniformly and accurately reflect the fact that we use the number of bytes expected to implement the join-count.

D.2 Introduction

The Cilk 2.0 run-time-system provides an execution environment for continuation-passing style threads written in the C programming language. The C code may be written directly by a human or it may be generated by a threaded-C preprocessor such as `cilk2c` (see Chapter 3.) This document specifies the run-time system. If you implement these functions then you should be able to run Cilk programs. If you generate correct calls to these functions, then your program will run on any compliant Cilk run-time-system.

The abstract programming model provided by Cilk is a dataflowlike procedure call tree, where each procedure consists of a collection of threads. The entire computation consists of a directed acyclic graph (DAG) of *threads*. A thread is a piece of code, implemented as a C function. Each thread runs only after all of its DAG predecessors have run. Each DAG predecessor of a thread can communicate with it by sending it some arguments. The DAG does not exist all at once. A program can build the DAG on the fly. Furthermore, the DAG is organized into *levels* according the procedure call tree. The procedure call tree has little to do with the C functions used to implement the program. Instead, C functions are used to implement threads. A *procedure* is collection of threads with some dependencies among them. The procedures themselves are threaded together via procedure-calls.

Rather than keeping track of the degree of each node in the DAG, our run-time system keeps track of something else called the *join-counter*. The join-counter is a variable kept for each closure. As each predecessor of a closure executes, the join-counter is decremented. Since the join counter can be decremented by any positive integer, the join-counter does not

[1]This chapter was written by Bradley C. Kuszmaul and Keith H. Randall.

specify the in-degree, but rather specifies the amount of decrementation that must occur before a thread runs.

The life cycle of a thread consists of

- Create the thread. When a thread is created, it is either created as a *child thread* (i.e, the thread is *spawned*) or a sibling thread.
- Modify the thread. After the thread is created and before it has been posted, it can be modified in various ways.
- Send values to the thread. As the predecessors of a thread execute, they send values to the thread, and decrement its join counter by appropriate values. Not every thread has values sent to it (in particular, a thread whose join-count is intially zero skips this step.)
- Post the thread. If the join-count of the thread is initially zero, then the thread is posted explicitly by the program. If the join-count of the thread is positive, then when enough values have been sent to the thread, the thread is posted automatically by the scheduler. A thread cannot be executed until it is posted. The closure can be moved to another processor only after it has been posted. A closure can be annotated ("*colored*") in various special ways, so that, for example, it will run on a specific processor.
- Execute the thread. After the thread has been posted, the thread can be run by the scheduler. The scheduler has some leeway about when it will actually run a thread, and it treats child threads differently from sibling threads (preferring to run a child before its parent, and to finish one child before starting another, although in the search for parallelism these rules may be relaxed.)
- Deallocate the storage for the thread. Note that is the responsibility of the thread code to deallocate its own closure before it returns. The runtime system does not automatically deallocate closures that have completed.

For certain threads, this lifecycle can be shortened. In particular for a thread that, as its last step, starts the execution of another thread (with in-degree of one), there is no need to invoke the scheduler. The C function can simply start executing the code for the next thread.

For certain programs we can guarantee space and time bounds, but we don't require the user to write such programs. Some of the requirements may be enforced by the scheduler. In particular, the scheduler is permitted to run a subtree without allowing other subtrees to make progress. Thus a non-strict program may deadlock. The current scheduler does not deadlock for such programs, but this specification allows us to write a scheduler that would deadlock. We expect to experiment with other schedulers in the future. In particular, we may eventually specify a scheduler that allows non-strict programs to run.

D.3 Data Types and Constants

Cilk employs three data types, visible to the user, to represent these computations.

- A *closure* is the data structure used to represent a vertex in the DAG of the program. A closure is represented by a contiguous block of memory, starting with some header information maintained by the implementation, followed by space for the arguments. The header is of type `ClosureT`, which is a structure typedef.
- A *continuation* is the data structure used to represent an incoming edge to a vertex of the DAG.
- A *thread* is the code which is run when a vertex of the DAG has been enabled.

Closures come in several *colors*, and have an extra integer associated with them, the *closure-info*. The colors are as follows:

`ClosureColorNormal`: A closure that can be stolen.[2]

`ClosureColorLocal`: A closure that must be executed on the same processor on which it was created.[3]

`ClosureColorPostNode`: A closure that must be executed on a particular named processor. The processor number is specified by the closure-info.

`ClosureColorMigrationThread`: A migration closure is the same as a `ClosureColorNormal` closure, except that it uses the closure-info field to specify how to move the closure to another processor. The closure-info field contains a pointer (cast into an `int`) to a C function, called the *packing routine*. The packing routine takes the closure as its only argument, and returns another closure. The argument closure may contain, for example, pointers into the heap. The returned closure must be flat (i.e., all the required data must be represented *by value* in the block of memory allocated to the closure. The returned closure's thread typically points to an unpacking routine to be executed at the remote processor (e.g., to convert the flat representation back into a data structure on the heap.) The packing routine should use `FreeClosure()` to deallocate its argument. The unpacking routine typically posts its new closure, using the original thread, and should color the new closure `ClosureColorLocal` in order to guarantee that the closure will not be moved again before it is actually executed. Thus we have

```
ClosureT *packer(ClosureT *closure);
```

Rationale: Yuli observed that we might want migration threads that are posted on specific nodes. Bradley thinks that if the user wants to post a thread on a specific

[2] The `ClosureColorNormal` color used to be called `STEAL`.

[3] The `ClosureColorLocal` color used to be called `NO_STEAL`.

node, then the user should make the closure flat to start with, rather than writing a migration thread to pack up a structure. The packing is valuable because it is done only when something is moved. If you know that the work will move, then just do the packing immediately.

`ClosureColorHandlerThread`: A closure that should be executed as soon as possible on a particular processor. In particular, once all the predecessors have run, we prefer to execute a `ClosureColorHandlerThread` closure before executing any non-`ClosureColorHandlerThread` closures. The closure-info specifies on which processor the closure must be executed.

One type qualifier appears frequently below: `CILK_INLINE` means that there is an inlineable version of the procedure.

D.4 Procedures

```
CILK_INLINE ClosureT *
  NewClosure ( ThreadT thread, int join_count, int size, int child_p );
```

effect: Create a new closure.

- The `join_count` specifies the initial join-count of the new closure. The value of `join_count` must be nonnegative. Note that even if `join_count` is zero, the closure is not posted into a ready queue.
- The `size` specifies the size of the closure block, measured in bytes. If you want to reserve space for n bytes of arguments, then call `NewClosure()` with the size set to `sizeof(ClosureT)` + n. The value of `size` must be no less than `sizeof(ClosureT)`.
- The `child_p` specifies whether the new thread belongs to this level (`child_p==0`) or to the next deeper level in the call tree (`child_p==1`). The value of `child_p` must be zero or one.

The beginning of the block of memory used to store the `size` bytes of arguments is available as a field `args` in the returned closure.

note: After creating the closure, but before posting the closure, you may set the closure color, the closure info (for certain colors), and fill in some of the argument memory of the closure.

```
CILK_INLINE void
  InitClosure ( ThreadT thread, int join_count, ClosureT *cp, int child_p );
```

effect: Create a closure by reusing a block of memory previously obtained from a call to `NewClosure()`. (Compare to `NewClosure()`, which creates a closure on a block of memory that the system newly allocates.) The `thread` specifies which thread will be run when the thread is posted and scheduled to execute. The `join_count` specifies the initial value of the join counter (just as for `NewClosure()`). The `child_p` specifies whether this is a sibling or spawned thread. The size of the closure is the same as the size of the original closure (and so, for example, do not try to modify the closure header to manipulate the size of the closure.)

`InitClosure()` allows the user to avoid the overhead of doing

```
FreeClosure(cp);
cp = NewClosure(...);
```

if both closures are the same size.

requires: The block must have been obtained by a previous call to `NewClosure()`.

```
CILK_INLINE void
  FreeClosure ( ClosureT *closure );
```

effect: Deallocates storage for this closure. All thread code should deallocate its closure before returning, unless it reuses the closure storage (with `InitClosure()`.)

requires: The closure must not be used in the future. This means, among other things, that the following must be true:

1. No memory loads or stores will, in the future, be made into the block of memory representing the closure (i.e., you should be finished using the closure fields);
2. No existing continuation pointing to this closure will be used in a SendArgument call in the future.
3. The closure is not currently posted anywhere. (That is, either the closure's join-count never went to zero, or else the thread associated with the closure has been run.)

```
CILK_INLINE void
  TailCall ( void );
```

effect: Notifies the run-time system that the C function has started executing another thread, and that the new thread is a child of the old thread. (There is no need to tell the scheduler that anything has happened if the new thread is a sibling of the old thread. The C function can simply start executing the new thread.)

```
CILK_INLINE void
  TailCallReturn ( void );
```

effect: Notifies the run-time system that the current C function has finished executing another thread. `TailCall()` and TailCallReturn() calls should bracket any direct call to another thread. For a "true" tail call (a `goto` to the beginning of the thread), this call is not needed because the tail call never returns.

```
CILK_INLINE void
  SetClosureColor ( ClosureT *closure, ClosureColorT color );
```

effect: Sets the color of the closure. The color of the closure determines how that closure will be posted when its join-count reaches zero. Setting the color to `ClosureColorX` tells the scheduler to post the closure with the `PostClosureX` routine (see below).

requires: The closure must not have been posted yet.

```
CILK_INLINE void
  SetClosureInfo ( ClosureT *closure, int info );
```

effect: Sets the closure-info of the closure. (Recall that closures of color `ClosureColorPostNode` and `ClosureColorHandlerThread` both use the closure-info to specify which processor the thread must be executed on. Closures of color `ClosureColorMigrationThread` use the closure-info to specify the packing routine. The closure-info is ignored for all other colors.)

requires: The closure must not have been posted yet.

```
CILK_INLINE void
  SetClosureThread ( ClosureT *closure, ThreadT *tp );
```

effect: Sets the thread (i.e., the C procedure) that will be run when the closure is executed.

requires: The closure must not have been posted yet.

```
CILK_INLINE void
  SetClosureJoin ( ClosureT *closure, int join );
```

effect: Sets the join counter of the closure. If you set the join counter to zero, you will need to manually post the closure.

requires: The closure must not have been posted yet, nor must the join counter have been manipulated by calls to a Send-Argument routine.

```
CILK_INLINE ContinuationT
  MakeContinuation ( ClosureT *closure, int index );
```

effect: Makes a continuation for the given index in the given closure. Index is an offset in bytes from the beginning of the closure.

usage note: We suggest the following strategy for making it easy to name the arguments, handle alignment issues, and otherwise manage the block of memory that holds a closure. Cast the value returned from `NewClosure()` to a structure pointer, for example:

```
typedef struct {
  ClosureT c;
  int x;
  char y;
  double z;
} CT007;
...
  { CT007 cl = (CT007*)NewClosure(&th, 2, sizeof(CT007), 0);
    ContinuationT c1
        = MakeContinuation(&cl->c, offsetof(CT007, x));
    ContinuationT c2
       = MakeContinuation(&cl->c, offsetof(CT007, z));
    cl->y = 'b';
...
```

```
CILK_INLINE ContinuationT
  IndexContinuation ( ContinuationT k, Word index, Word size );
```

effect: Make a new continuation from an old continuation and an offset (where the offset is specified as index into an array of elements, each of size `size`). If `k` was created with offset `i` in a closure, then `IndexContinuation(k,j,s)` has offset $\texttt{i} + \texttt{j} \cdot \texttt{s}$ in the same closure. That is,

`IndexContinuation(MakeContinuation(c,i),j,s)` $\equiv_{\text{def}}$ `MakeContinuation(c,i+j*s)`.

```
CILK_INLINE void
  PostClosure ( ClosureT *closure );
```

effect: Posts the specified closure. If you know the color of the closure, then higher performance can be obtained by calling the appropriate specialized posting routine described below.

requires: The color (and the info, if used by that color), must be set.

note: The scheduler may use `PostClosure()` to post a closure when its join count goes to zero.

```
CILK_INLINE void
  PostClosureNormal ( ClosureT *closure );
```

effect: Sets the color of `closure` to be `ClosureColorNormal` and posts it.

```
CILK_INLINE void
  PostClosureLocal ( ClosureT *closure );
```

effect: Sets the color of `closure` to `ClosureColorLocal` and posts it.

```
CILK_INLINE void
  PostClosureNode ( ClosureT *closure, int pn );
```

effect: Posts a `ClosureColorPostNode` closure, and guarantees that the closure will executed only on the processor specified by `pn`. This is done by setting the closure's color to `ClosureColorPostNode` and the closure's info field to `pn`.

```
CILK_INLINE void
  PostClosureHandler ( ClosureT *closure, int pn );
```

effect: Sets the color of `closure` to `ClosureColorHandlerThread` and posts it so that it will run on processor `pn`. (This is done by setting the closure's info field to `pn`.)

```
CILK_INLINE void
  PostClosureMigration (ClosureT *cp, MigrationT mt );
```

effect: Sets the color of `closure` to `ClosureColorMigrationThread` and posts it. The closure's info field is set to be the `mt`.

issue: Need to define `MigrationT`.

```
CILK_INLINE void
  SendCharArgument ( ContinuationT continuation, char value );
```

effect: Send an 8-bit value to a continuation (decrementing the join counter of the closure, and posting the closure if the join-count becomes zero.)

```
CILK_INLINE void
  SendShortArgument ( ContinuationT continuation, short value );
```

effect: Send a 16-bit value to a continuation (decrementing the join counter of the closure by 2, and posting the closure if the join-count becomes zero.)

requires: The `continuation` must have been created with a 16-bit aligned `index`. (I.e., the `index` used for `MakeContinuation` must have been zero modulo 2.)

```
CILK_INLINE void
  SendWordArgument ( ContinuationT continuation, Word value );
```

effect: Send a 32-bit value to a continuation (decrementing the join counter of the closure by 4, and posting the closure if the join-count becomes zero.)

requires: The `continuation` must have been created with a 32-bit aligned `index`. (I.e., the `index` used for `MakeContinuation` must have been zero modulo 4.)

```
CILK_INLINE void
  SendDoubleWordArgument ( ContinuationT continuation, DoubleWord value );
```

effect: Send a 64-bit value to a continuation (decrementing the join counter of the closure by 8, and posting the closure if the join-count becomes zero.)

requires: The `continuation` must have been created with a 64-bit aligned `index`. (I.e., the `index` used for `MakeContinuation` must have been zero modulo 8.)

```
CILK_INLINE void
  SendFloatArgument ( ContinuationT continuation, float value );
```

effect: Send a 32-bit floating-point value to a continuation (decrementing the join counter of the closure by 4, and posting the closure if the join-count becomes zero.)

requires: The `continuation` must have been created with a 32-bit aligned `index`. (I.e., the `index` used for `MakeContinuation` must have been zero modulo 4.)

```
CILK_INLINE void
  SendDoubleArgument ( ContinuationT continuation, double value );
```

effect: Send a 64-bit floating-point value to a continuation (decrementing the join counter of the closure by 8, and posting the closure if the join-count becomes zero.)

requires: The `continuation` must have been created with a 64-bit aligned `index`. (I.e., the `index` used for `MakeContinuation` must have been zero modulo 8.)

```
CILK_INLINE void
  SendArrayArgument ( ContinuationT continuation, char *array, int length );
```

effect: Send a block of memory to a continuation (decrementing the join counter of the closure by `length`, and posting the closure if the join-count becomes zero.) If the `length` is zero, the pointer `array` is not dereferenced. The `SendArrayArgument()` function can be used to send both structures and arrays.

note: The size of the data being sent must be the same as (or less than, if the data is being sent peicemeal) the size of the return type of the thread specified in the thread signature table. This should not cause a problem for structures, but one must be very careful with arrays.

requires: The value of `length` must not be larger than the remaining join count.

```
CILK_INLINE void
  Signal (ContinuationT k);
```

effect: This routine sends a *signal* to a closure. A signal is a just like any other Send-Argument routine, except no data is sent. The join-count is decremented by 1, and if it becomes zero, the closure is posted.

```
CILK_INLINE void
  AccumulateWord (ContinuationT k, AccumWordOp op, int delta);
```

effect: The closure memory element specified by the continuation `k` is modified according to `op` and `delta`. That is, if `a` points to the address referenced by the continuation `k`, then this routine calls

```
(*op)(&delta,a);
```

The closure's join count is decremented by 4, and if it becomes zero, the closure is posted.

The Cilk system provides the following predefined functions.

`accum_word_add`: (addition)

`accum_word_mul`: (multiplication)

`accum_word_and`: (bitwise logical 'and')

`accum_word_or`: (bitwise logical 'or')

`accum_word_max`: (signed maximum)

`accum_word_min`: (signed minimum)

For example, `accum_word_add` could have been defined as

```
void accum_word_add (int *v, int *a)
{
  (*a) += *v;
}
```

The user can also define and use his or her own accumulation operations.

requires: The continuation `k` must have been created with an index that is sufficiently aligned that the function `op` can access it without causing trouble. The system-defined operations require 32-bit alignment.

note: AccumWordOp is defined as:

```
typedef void (*AccumWordOp) (long *new, long *accum);
```

```
CILK_INLINE void
  AccumulateDoubleWord (ContinuationT k, AccumDoubleWordOp op, long long delta);
```

effect: The closure memory element specified by the continuation `k` is modified according to `op` and `delta`. That is, if `a` points to the address referenced by the continuation `k`, then this routine calls

```
(*op)(&delta,a);
```

The closure's join count is decremented by 8, and if it becomes zero, the closure is posted.

The Cilk system provides the following predefined functions.

`accum_doubleword_add`: (addition)

`accum_doubleword_mul`: (multiplication)

`accum_doubleword_and`: (bitwise logical 'and')

`accum_doubleword_or`: (bitwise logical 'or')

`accum_doubleword_max`: (signed maximum)

`accum_doubleword_min`: (signed minimum)

requires: The continuation `k` must have been created with an index that is sufficiently aligned that the function `op` can access it without causing trouble. The system-defined operations require 64-bit alignment.

note: AccumDoubleWordOp is defined as:

```
typedef void (*AccumDoubleWordOp) (LONG_LONG *new, LONG_LONG *accum);
```

```
CILK_INLINE void
  AccumulateFloat (ContinuationT k, AccumFloatOp op, float delta);
```

effect: The closure memory element specified by the continuation `k` is modified according to `op` and `delta`. That is, if `a` points to the address referenced by the continuation `k`, then this routine calls

```
(*op)(&delta,a);
```

The closure's join count is decremented by 4, and if it becomes zero, the closure is posted.

The Cilk system provides the following predefined functions.

`accum_float_add`: (addition)

`accum_float_mul`: (multiplication)

`accum_float_max`: (maximum)

`accum_float_min`: (minimum)

requires: The continuation `k` must have been created with an index that is sufficiently aligned that the function `op` can access it without causing trouble. The system-defined operations require 32-bit alignment.

note: AccumFloatOp is defined as:

```
typedef void (*AccumFloatOp) (float *new, float *accum);
```

```
CILK_INLINE void
  AccumulateDouble (ContinuationT k, AccumDoubleOp op, double delta);
```

effect: The closure memory element specified by the continuation `k` is modified according to `op` and `delta`. That is, if `a` points to the address referenced by the continuation `k`, then this routine calls

```
(*op)(&delta,a);
```

The closure's join count is decremented by 8, and if it becomes zero, the closure is posted.

The Cilk system provides the following predefined functions.

`accum_double_add`: (addition)

`accum_double_mul`: (multiplication)

`accum_double_max`: (maximum)

`accum_double_min`: (minimum)

requires: The continuation `k` must have been created with an index that is sufficiently aligned that the function `op` can access it without causing trouble. The system-defined operations require 64-bit alignment.

note: AccumDoubleOp is defined as:

```
typedef void (*AccumDoubleOp) (double *new, double *accum);
```

```
int
  RunScheduler ( int mode, ThreadT root_thread, int num_args, ... );
```

effect: Starts up the scheduler and runs the thread `root_thread` with `num_args` words of arguments, returning the return value of `root_thread`. Note that `num_args` (and the argument list) does NOT include the continuation which must be the first argument of `root_thread`. This continuation will be provided by RunScheduler. Note that this is a data-parallel operation so all processors involved must call it. (All arguments except `mode` are ignored on processors where `Self` $\neq 0$). Work-stealing is enabled if mode is `CILK_AUTO` or `CILK_AUTO_KEEP`, and the heap is kept around upon return if mode is `CILK_AUTO_KEEP` or `CILK_MANUAL_KEEP`.

requires: The value of `mode` must belong to the enumeration type

```
enum run_mode { CILK_AUTO, CILK_MANUAL, CILK_AUTO_KEEP, CILK_MANUAL_KEEP };
```

All processors must call `RunScheduler()` at about the same time.

The value of `cilk_active_size` must be valid.

An alternative means of starting the scheduler uses the functions `InitScheduler()` and `EnterScheduler()`.

issue: I need to define `Self`.

issue: Bradley believes that the specification of this routine needs to be rewritten. For example, what do we mean by "about the same time"?

```
void
  InitScheduler ( void );
```

effect: Initializes scheduler data structures so that closures can be created.

Typically used with `NewClosure()` and `EnterScheduler()` in the following sequence:

```
InitScheduler ();
root_closure = NewClosure(...);
/* initialize arguments in root_closure here */
EnterScheduler (root_closure, &result, sizeof(result));
```

```
void
  EnterScheduler ( ClosureT *root_closure, void *result, int result_size );
```

effect: Starts up the scheduler and runs the closure `root_closure`. The return value of `root_closure` is placed in the `result_size` bytes of memory addressed by `result`. (If `root_closure` returns `void`, then `result` and `result_size` should both be 0.) Note that the first argument in `root_closure` must be an uninitialized continuation, which is initialized by EnterScheduler. Like RunScheduler, this is a data-parallel operation so all processors involved must call it. (All arguments are ignored on processors where `Self` $\neq 0$). Work-stealing is enabled if the global variable `cilk_mode` is `CILK_AUTO` or `CILK_AUTO_KEEP`, and the heap is kept around upon return if `cilk_mode` is `CILK_AUTO_KEEP` or `CILK_MANUAL_KEEP`.

requires: Any call to this function must be preceded by a call to `InitScheduler()`.

All processors must call `EnterScheduler()` at about the same time.

The values of `cilk_active_size` and `cilk_mode` must be valid.

An alternative means of starting the scheduler uses the function `RunScheduler()`.

issue: I need to define `Self`.

issue: Bradley believes that the specification of this routine needs to be rewritten. For example, what do we mean by "about the same time"?

```
void
  CilkInit( int *argc, char *argv[] );
```

meaning: Initializes Cilk and any communication libraries that Cilk uses, and parses any Cilk command-line arguments. When `CilkInit` returns, it removes any Cilk command-line arguments from `argv` and updates `argc` appropriately.

```
void
  CilkExit( int exitcode );
```

meaning: Ends the Cilk program. If `Exitcode` is zero, this is a normal exit and the processor that calls it will wait for the others to finish. If `exitcode` is non-zero, it is an error exit. (all processors will exit if any processor calls `CilkExit` with a non-zero argument.) This should be called after `RunScheduler` returns.

```
  extern int cilk_active_size;
```

meaning: The variable `cilk_active_size` specifies how many processors the user actually wants to use. The user can set this variable before calling `RunScheduler()`. The value must be a nonnegative value no greater than the number of actual processors. A zero value is used to specify as many processors as are actually available. A positive number specifies a particular number of processors to use.

The user may want to specify just a few processors in order to obtain data about the performance of his or her application as the number of processors is varied.

default: This variable defaults to the number of available processors.

```
enum run_mode { CILK_AUTO, CILK_MANUAL, CILK_AUTO_KEEP, CILK_MANUAL_KEEP };
extern int cilk_mode;
```

meaning: The variable `cilk_mode` specifies whether work-stealing should be enabled, and whether the scheduler heap is kept around after the scheduler returns. Work-stealing is enabled if the global variable `cilk_mode` is `CILK_AUTO` or `CILK_AUTO_KEEP`, and the heap is kept around upon return if `cilk_mode` is `CILK_AUTO_KEEP` or `CILK_MANUAL_KEEP`.

This variable may not be changed while the scheduler is running.

default: `CILK_AUTO`.

```
extern int cilk_serial;
```

meaning: The variable `cilk_serial` indicates whether the `-serial` option was present on the command line. Its value is 1 if `-serial` was present, 0 otherwise.

This variable is used by the standard `main` to determine whether `cilk_main` should be scheduled in parallel or called serially. A user-written `main` may wish to use `cilk_serial` for the same purpose, to choose between parallel and serial (or SPMD) versions of an algorithm.

```
extern void (*cilk_user_function)();
extern int n_threads_per_user_function;
```

meaning: The function `cilk_user_function` will be called periodically on each node by the scheduler so that the user may perform some periodic tasks. This function will be called more often if the value of `n_threads_per_user_function` is smaller. Both of these global variables must be set before the call to `RunScheduler`. They may have different values on different processors. Use `NULL` for the cilk_user_function in order to disable this feature.

default: `cilk_user_function` defaults to `NULL` and `n_threads_per_user_function` defaults to 20.

requires: These variables must not be modified by the user while the scheduler is running.

```
extern int migration_dest_node;
```

meaning: This variable holds the processor number of the destination processor for a migration thread. It is only valid inside migration handlers.

issue: This is used in the chess code for aborts. Is it useful as a general mechanism? Should we expose it?

Appendix E

Cilk Runtime System Implementor's Guide

In order to port Cilk to your architecture, you need a standard ANSI C compiler; we recommend `gcc`, which was used for development and whose extensions are supported. The port is divided in three main phases: in the first one Cilk is compiled to run on just one processor, the second step brings up a full parallel Cilk and finally in the third step you provide the code to enable accurate timing measurements for Cilk.

E.1 First step: get a sequential version of Cilk running

Your first task is to get Cilk running on your architecture without any of the work stealing and parallel code. This is very simple, since Cilk is written in ANSI C and requires no particular support from the underlying operating system or compiler: however some `gcc` extensions are supported in order to have better performances. First, choose a name for your architecture (e.g. `CM5`, or `PARAGON`) and edit the file `rts/conf.h`. This file contains some options you are expected to define in this first step.

Create a block of definitions just before the section marked `Statistics & Debugging` similar to the prototype included in the file. There are some options you might want in order to get a different behavior or better performance:

`IS_PARALLEL` Leave this option off for the moment. Enabling this option causes work stealing code to be compiled, and this requires your intervention. Wait until step 2 to turn this on.

`HAVE_LONG_LONG` Turn this on if your compiler supports very long integers (64 bits); also `typedef LONG_LONG` to be the C type of these integers (probably `long long`). `gcc` supports this type.

`CILK_ALIGNMENT_TYPE` This must be set to the `C` type with the most stringent alignment requirements on your architecture. For examples, if your `int`s are 4-bytes aligned and your `double`s are 8-bytes aligned, define this macro to be `double`.

[1] This chapter was written by Matteo Frigo.

`CILK_PRINTF` This is a `printf`-like function Cilk uses for its diagnostic messages, statistics and such. `#define CILK_PRINTF printf` is probably good if your `printf` doesn't clobber the network with messages. Otherwise you have to write your own function.

`CONTINUATION_HACK` Turn this option on if you have the `LONG_LONG` type and want to pack continuations to fit into this type. Otherwise, leave this option off. This option will allow the compiler to register-allocate continuations.

`HAVE_INLINE` Turn this option on if your compiler supports `inline` functions and you want to use them. There is a speedup for using this option, at expense of increased code size.

`CILK_ARCH_H` Define this to be the name of the architecture-specific header file.

There are some more options you can define. It's advisable to have `CILK_SELFTEST==1` (this enables lots of consistency checks, valuable for debugging). `CILK_TRACE` enables some useful diagnostic output; the semantics of `CILK_TRACE` is as follows: a value of 0 disables the diagnostic output completely; any other value enables tracing, and the value of `CILK_TRACE` becomes the default *tracing mode*. The tracing mode is an unsigned integer which can be set from a command line option. The bits of the tracing mode are significant, and they enable tracing of different subsystems of Cilk. Look at `rts/macros.h` for an explanation of the meaning of each bit. If the tracing mode is 1, then tracing is enabled but no output is produced; this can therefore be a good default value.

Now you must create two files, `rts/arch-your_arch.c` and `rts/arch-your_arch.h`. In the `.h` file put something like

```
#define CILK_LONG_ALIGNMENT 4
#define CILK_SHORT_ALIGNMENT 2
#define CILK_LONG_LONG_ALIGNMENT 8
#define CILK_FLOAT_ALIGNMENT 4
#define CILK_DOUBLE_ALIGNMENT 8
```

The goal of these macros is to provide means of allocating variables without violating architectural requirements for alignment of variables. The definitions given should be good for most processors in use today. If you haven't got `LONG_LONG`, you don't need to define the corresponding alignment.

Also insert something like

```
#define CRITICAL_SECTION_BEGIN()
#define CRITICAL_SECTION_END()
```

These macros will not be used until later stages, but should be defined now in order to avoid compilation errors. You can start by making a copy of `rts/arch-sunos4.h` to have all these definitions in the right place.

Take the time to define the macro `Cilk_FlushStdout()`: this should make sure that all diagnostic messages are actually output, and internal buffers of `CILK_PRINTF` are emptied. Probably

```
#define Cilk_FlushStdout() fflush(stdout)
```

would suffice.

Then you must edit `rts/arch-your_arch.c` to be something like

```
#include <cilk.h>

int Self;

int Cilk_ArchSpecificInit(int argc, char *argv[], int i)
{
     Cilk_PartitionSize = /* the number of processors you're running on */
     Self = /* the number of the local processor */
     /*
      * parse here architecture-specific command-line options,
      * starting from argv[i] and making sure that after the parsing
      * argv[i] is the first non-Cilk argument.
      */
     return i;
}

void Cilk_ArchSpecificExit(int status)
{
     exit(status);
}
```

Again, `rts/arch-sunos4.c` is a good example to start with. If your machine has only one processor, just let `Cilk_PartitionSize=1` and `Self=0`.

Now edit the `Makefile` to provide suitable flags to the C compiler. These flags should be added as `YOUR_ARCHITECTUREFLAGS` after the `UNIXFLAGS` definition. You should be sure to define your architecture's flag to be 1 (i.e., include the flag `-DYOUR_ARCHITECTURE=1` in your flag list). Also, you must add libraries for your machine to the `libraries` list. A good way to do this is to replace `cm5` with your architecture in the `libraries` rule and in the following four `libCilk` rules. This replacement will allow you to build libraries for your architecture as well as a standard Unix architecture. You must also change some of the rules in the `building executables` and `building binaries` to reflect your architecture's linking and compilation rules. Be sure to use `YOUR_ARCHITECTUREFLAGS` in the `building binaries` section. Finally, you should also make the same changes to the `Makefile` in the examples directory.

Now compile everything and go to the `examples` directory. You should be able to compile and run all files. Try `fib 25`, whose expected result is 75025, and `queens 8` (92 is the correct result). If you have `gcc` you should be able to compile and run `rts/testall.cilk`.

E.2 Second step: get a work-stealing scheduler running

If you machine is sequential, go to step 3. Otherwise enjoy: unlike the first stage, this stage requires some ingenuity and creativity . You will need to write code yourself, rather than simply cutting and pasting existing code. You'll demonstrate your ability to write compact, elegant and efficient code for the Cilk Runtime System!

First of all, turn on the option `IS_PARALLEL` in `conf.h`. Having done that, everything that can go wrong will go wrong, so you'd better enable the tracing subsystem (`#define CILK_TRACE 1`).

Overview of what needs to be done. You must now implement two protocols, called *work stealing* and `PostClosureNode`[2]. We begin with a short description of these two protocols, and then we explain the implementation in two possible scenarios.

The work stealing protocol is as follows: when the Cilk scheduler on processor `src_pn` has no ready closures to execute, it invokes the function `steal()`. That function chooses a random processor `dest_pn`, sets up some buffers for receiving the stolen closure and sends a message to `dest_pn`. When `dest_pn` receives the steal request, it invokes the function `get_stealable_closure()` to get a closure suitable to be stolen. There are now two possibilities: if such closure exists, it is sent back to `src_pn`; otherwise a message is sent to `src_pn` indicating the failure.

A naïve approach to `PostClosureNode` is simply to take the closure and send it to the destination processor. As stated, however, this protocol is flawed, in the sense that it could deadlock if two processors try to send a closure to each other and neither reads incoming messages from the network. We know of machines such as the Intel Paragon, however, in which incoming communication is managed by the operating system and messages are stored in buffers if the user program is not expecting them, and thus the simple protocol is adequate. Unfornately the Strata library for the CM5 does not offer such a luxury, and we use a different protocol, as follows. Let's call `src_pn` and `dest_pn` respectively the source and destination processors. `src_pn` sends a "request to send" message to `dest_pn`, upon reception of which `dest_pn` allocate a buffer to receive the incoming closure, and tells the communication library to store the incoming message in that buffer. In the meantime `src_pn` is ready to process incoming messages. After that, `dest_pn` sends back a "clear to send" message to `src_pn`, the reception of which causes `src_pn` to actually send the closure.

Cilk abstracts the protocols in terms of remote procedure calls, and your goal is to provide a mechanism to invoke a procedure on a remote processor.

Implementation strategy for Remote Procedure Calls. We describe two possible implementations of the above protocols. In the first scenario incoming messages need to be polled explicitly; in the second case messages are received and the reception causes an user-defined function to be invoked. *Important warning: there is some provision for this second scenario, but it has never been tested.*

[2] If you made a port of Cilk 1.x you will appreciate the great overall simplification of the porting strategy.

```
long buf[10];   /*
                 * or whichever is the maximum length of message
                 * you are sending.
                 */

void Cilk_POLL(void)
{
     while (test()) {
          /* receive the message into buf */
          receive(buf);

          /* can't understand what's going on? This is equivalent
           * to:
           *
           * void (*fp)(long *) = (appropriate cast) buf[0];
           * (*fp)(buf);
           */
          (*(void (*)(long *))buf[0])(buf);
     }
} /* that's all the dispatcher */
```

Figure E.1: Skeleton code for `Cilk_POLL`

In the *first case* (explicit polling), our advice is to emulate the CM5 active-messages layer, in the following way. An *active message* is, for our purposes, a message whose first field is a pointer to a function, and whose remaining fields are the arguments to that function. You must write a function called `Cilk_POLL()` which tests for incoming messages, reads the message and invokes the function specified by the first field of the message with the message itself as an argument. The figure E.1 shows a skeleton code for `Cilk_POLL()`, while figure E.2 displays a typical invocation of a remote procedure.

In the *second case* (asynchronous messages) you should do whatever your communication library needs in order to invoke a function on a remote processor. In addition `CRITICAL_SECTION_BEGIN()` and `CRITICAL_SECTION_END()` should be defined in such a way that they disable, and respectively enable, the reception of messages. Also `Cilk_POLL()` should be `#defined` to be empty.

Now provide barriers. In Cilk's jargon, a *barrier* is a synchronization point: the goal of a barrier is to make sure that a processor can cross the barrier only when *all* processors have reached it. You must define a function (or macro) `void Cilk_Barrier(void)` to do exactly this job: this function is probably already implemented in one of you system libraries. No special properties are required from a barrier: it doesn't need to poll for incoming messages or allow interrupts to occur (it can do these things if it wishes). We'd like to hear from you if

```
struct foo_message { void (*fp)(long *); int arg; };

void foo(long *buf)
{
     int arg = ((struct foo_message *) buf)->arg;
     /* body of foo */
}

void invoke_foo(int dest_pn, int arg)
{
     struct foo_message b;
     b->fp = &foo;
     b->arg = arg;
     send(dest_pn, b);
}
```

Figure E.2: Example usage of remote procedure calls

you find any difficulty in implementing barriers (i.e. if your system doesn't already provide such functionality): we can design a general mechanism for making barriers using RPCs if they are not easily implementable.

Implement work-stealing. The work-stealing protocol has been described above; now we give a description of the various functions Cilk uses for work stealing and that you must provide (in the architecture-specific `.c` file); you must write the following five functions: `Cilk_setup_for_steal`, `Cilk_invoke_steal_handler`, `Cilk_reply_steal_failure`, `Cilk_send_stolen_closure()` and `Cilk_receive_stolen_closure`.

`void Cilk_setup_for_steal(int dest_pn)` is invoked before any steal request. It must do whatever initialization is necessary (for example, allocate a buffer for the incoming closure, tell the operating system that a message is coming, and so on).

`void Cilk_invoke_steal_handler(int dest_pn)` is used by the thief to post a steal request on `dest_pn`. This function must cause `Cilk_steal_request_handler(int src_pn)` (provided by the Cilk RTS) to be executed on `dest_pn`. `src_pn` is the processor number of the thief.

In case of steal failure, `Cilk_reply_steal_failure(int pn)` is invoked; this function must cause the execution of `Cilk_steal_failure_handler` on processor `pn`.

Otherwise the victim calls `Cilk_send_stolen_closure(ClosureT *cp, int pn)`: it sends the closure pointed to by `cp` to processor `pn` *and* executes `Cilk_steal_success_handler` on `pn` itself, with a single integer argument indicating the processor which the closure was stolen from. Finally, you must define `Cilk_receive_stolen_closure(void)` (executed on the thief) which returns a pointer to the incoming closure. If you are using `Cilk_POLL()`, there are at least a couple of ways to implement these functions. One pos-

sibility is to build a big message containing a pointer to `Cilk_steal_success_handler` and the closure. `Cilk_POLL()` will take care of invoking the handler, and in this case `Cilk_receive_stolen_closure` simply returns the pointer to the buffer. Another possibility is to send two distinct messages, and have `Cilk_receive_stolen_closure` receive the incoming closure.

Implement `PostClosureNode`. There are just two functions required by the Runtime System for the `PostClosureNode` protocol.

The first function is `void Cilk_remote_postclosure(ClosureT *cp, int pn)`; its goal is to send the closure pointed to by `cp` to processor `pn`; moreover, when the transfer is completed, `Cilk_remote_post_final(ClosureT *cp, int from_whom)` must be invoked on the destination processor `pn`, in order to make Cilk aware of the new closure.

`Cilk_remote_postclosure` can be asynchronous, i.e. it can return before the transmission has been completed; however sometimes Cilk needs to be sure that all outgoing closures have been sent; this is the goal of the second function, namely

```
int Cilk_ArchSpecific_ready_to_exit(void),
```

which returns any nonzero value if all protocols have been completed. Currently Cilk has just two protocols, and work stealing is cleared explicitly by Cilk; therefore this function needs only to report the status of outgoing post requests.

After writing the protocols. `testall` is the right program to run now, if you have `LONG_LONG` (sorry for that, a more portable `testall.p` will be released in some next version). And again, all examples should run fine: try `tree 14`, and expect $2^{14} = 16384$ leaves.

E.3 Step three: add time statistics

This step isn't really needed for full functionality of Cilk; however having these kinds of statistics is a good thing anyway, and you should dedicate some time to make them work, once and forever.

Cilk supports two kind of time measurements: a coarse-grained timing of the total execution and a fine-grained measurement of the execution time of each thread, which is used to determine the critical path and the work done by every processor.

Total execution time. In order to have a measurement of the execution time, you are required to edit `rts/conf.h`, enable the option `CILK_ELAPSED_TIME` and define two functions or macros in the architecture-specific files:

`void Cilk_TimerStart(void)` This function should start a machine-dependent timer (or record the current time somewhere).

`double Cilk_TimerStop(void)` This function returns the time (in seconds) elapsed since the last call to `Cilk_TimerStart()`.

Critical-path and work. Make sure that you have a very accurate clock on your machine (with a resolution of one μs or more) and make sure that reading it won't cost too much time (this operation is going to be executed millions of times). If the only way to read the clock is to issue a system call you are out of luck.

If your system satisfies these requirements, enable the option `CILK_TIMING` in the file `rts/conf.h`. Establish a time unit (for example a μs, or a CPU cycle) that is suited to your architecture. Cilk can handle whatever unit you choose, since it represents time as multiples of this unit, called a *cycle* in Cilk's jargon. Cilk's time is stored into a `unsigned long`: make sure that the execution time of a thread doesn't overflow the counter (100 ms is a reasonable maximum time for a thread).

Now you you must provide the following macros or functions:

`unsigned long Cilk_CycleCount(void)`: This function returns the current time, in cycles.

`unsigned long Cilk_PackCycles(unsigned long n)`: This function is used to collect the critical path timings, and its goal is twofold: I) to change the time scale so that the critical path time can still be held by an `unsigned long` without overflow (in practice it performs a division of `n` by some power of 2), and II) to adjust `n` to prevent errors. There is a problem on the CM5 (and possibly on other architectures), in that the system clock measures real-time; however the machine is timeshared, and a thread can be interrupted by the operating system. In this case the cycle counter measures the execution time for a thread plus the time quantum in which another process has been executed. We therefore adopt the heuristic that a thread is considered broken if that thread ran for more than 50 ms, and if a thread is broken, we give it a zero execution time.

`unsigned long Cilk_AdjustCycles(unsigned long n)`: This macro must adjust `n` to prevent errors, but not change the time scale.

`double Cilk_UnpackCycles(unsigned long n)`: Performs the opposite action, i.e. converts from packed cycles to cycles. The result is a `double`, since it could overflow a `long`.

`Cilk_CyclesToSeconds(n)`: This macro (it should be a macro for technical reasons, since the type of `n` varies) converts from cycles into seconds. In practice it divides `n` by the number of cycles per second. The result must be cast to `double`.

Appendix F

Notes on Compiling Cilk

This section outlines the basic runtime assumptions and compilation schemes for Cilk procedures and threads, which may be useful to those wishing to understand more about Cilk implementation or the C code generated by the Cilk compiler.

F.1 Notes to Cilk 1.x Users

For those familiar with version 1.x of Cilk, a procedure is like an extended thread with an implicit first argument that is the return continuation. In addition it allows the programmer to specify successor threads in-place after the sync statement. The closure of the thread, i.e. the frame of the procedure, is re-used by the successor threads when they get enabled. Due to the above reason, essentially no runtime system changes are needed to support procedures.

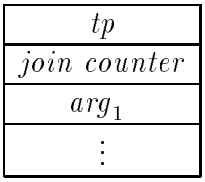
Continuation-passing linkage is implicit in procedure invocation and return, being generated automatically by the Cilk compiler. The standardized linkage is also more restricted, thus does not offer the full flexibility of threads in explicit continuation-passing style. However, we firmly believe in the convenience the procedure abstraction provides to the programmer, and feel that it should also be sufficient for the majority of programming tasks. In order to handle extremely demanding applications, threads are still supported as a subset of the language (see section 2.4).

F.2 Closures and Frames

Closures and frames are the basic units managed by the runtime scheduler. A closure contains a thread pointer, slots for all thread arguments, and a join counter that indicates the number of outstanding arguments[2]

[1] This chapter was written by Yuli Zhou.

[2] In current implementation the value of a join counter records the number of bytes the closure will receive before it is ready to execute.

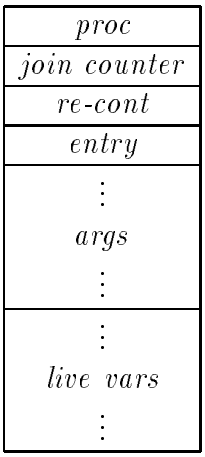


Continuations are created as global references to argument slots to enable one thread to send arguments to another, with an implied synchronization operation to decrement the join counter and post the closure to the scheduler in case the join counter becomes 0.

The Cilk compiler generates two C functions for each thread. The first is a general version that takes the closure as the only argument, and is invoked from the scheduler. In other words, this is the function that has the name *tp* that is stored in the closure. Additional code to fetch the argument from the closure is generated by the Cilk compiler and inserted before the specified body of the thread.

The second C function is a fast version that takes all arguments directly. This is the functions that gets called when a thread is invoked via the `call` family of keywords.

A frame is a special closure that is shared by successor threads. However, instead of splitting a procedure into multiple non-blocking threads we have adopted a compilation scheme based on re-entering the same function at various resumption points. A frame has the following format:



where *proc* and *entry* indicates the point of initial entry or resumption after a sync. A single join counter is used to register the number of spawned child procedures that have not yet returned. The return continuation *re-cont* consists of a pointer to its parent frame, and an offset into a frame slot waiting for the return value.

The above frame format is compatible with that of the closure for threads, thus allowing procedures to be implemented on the old runtime system essentially without change to the latter.

The Cilk compiler generates two C functions for each procedure. One of the functions is just a sequential version of the procedure by stripping the parallel keywords `spawn` and `sync`. The other function is the parallel version that takes one argument, which is a pointer to its own frame. This function uses the `entry` field in the frame for an indexed jump into each resumption point after being suspended at a sync:

```
void foo (frame *fp)
{
   switch (fp->entry) {
      case 0:  goto L0;
      case 1:  goto L1;
      ...
   }
L0:/* point of initial entry */
   ...
   /* sync expands into context switching code */
   if (--fp->join-counter != 0) {
      [save live variables that are modified]
      fp->entry = 1;
      return; /* to scheduler */
   L1:/* point of resumption after the sync */
      [restore free variables]
   }
   ...
}
```

Each sync in the procedure expands into context switching code, which is conditionalized on `join-counter == 0` to allow falling-through over the sync. Note that to insure the join counter do not become 0 prematurely, we initialize it to `1` instead of `0`, and decrement it by `1` when the sync is reached.

Appendix G

Release Notes

G.1 Release 2.0 Beta 1

- SendArrayArgument is back!
- New language supports procedures, typed continuations, and mixed C and Cilk code. See Appendix H for more details.
- New type-checking preprocessor, *cilk2c*, replaces *cilkpp*.
- Added stubs to run-time system.
- Major portability changes will make it easer to port Cilk to other platforms.

G.2 Release 1.2 Beta 1

- Fixed a bug where closures created with a zero-size accumulator were not being correctly posted.
- Added DoubleWord accumulators:

```
AccumulateDoubleWord (cont k, AccumDoubleWordOp op, long long delta);
accum_doubleword_add (doubleword value, doubleword *accum);
accum_doubleword_mul (doubleword value, doubleword *accum);
accum_doubleword_and (doubleword value, doubleword *accum);
accum_doubleword_or (doubleword value, doubleword *accum);
accum_doubleword_max (doubleword value, doubleword *accum);
accum_doubleword_min (doubleword value, doubleword *accum);
```

- Added `float` and `double` types to primitive communication operations. In particular, the following routines were added:

```
SendFloatArgument (cont k, float value);
SendDoubleArgument (cont k, double value);
AccumulateFloat (cont k, AccumFloatOp op, float delta);
AccumulateDouble (cont k, AccumDoubleOp op, double delta);
accum_float_add (float value, float *accum);
accum_float_mul (float value, float *accum);
accum_float_max (float value, float *accum);
accum_float_min (float value, float *accum);
accum_double_add (double value, double *accum);
accum_double_mul (double value, double *accum);
accum_double_max (double value, double *accum);
accum_double_min (double value, double *accum);
```

G.3 Release 1.1 Beta1

Syntax changes over version 1.0 beta2. The statement form that spawns a thread is changed from

```
spawn (foo, args ...) stmt
```

to

```
spawn foo (args ...) stmt
```

The same changes apply to all cousins of `spawn`, i.e., `spawn_next`, `call`, `call_next`, `tail_call`, `tail_call_next`, `make_closure` and `make_next_closure`. (See the changed example programs.)

G.4 Release 1.0 Beta2

The first public release.

Appendix H

Language Changes

H.1 From Version 1.2 to 2.0

New to version 2.0 are Cilk procedures, threads exist only as a backward compatibility mode and a lower-level mechanism. Usage of thread syntax is therefore discouraged where the procedure syntax is sufficient. See the language reference manual for the new procedure syntax and how procedures connects with the old thread syntax.

The new-style entry into the scheduler is through the `cilk_main` procedure or the `schedule` construct. As the `schedule` construct does not allow a mode parameter, the global variable `cilk_mode` is provided.

The remainder of this section gives requirements and suggestions for porting your Cilk 1.2 programs to Cilk 2.x. The hints here are sorted along two dimensions. Changes which are expected to affect the most programs are listed in the first section, "Major Changes"; the rest are listed in the second section, "Minor Changes". Within each section, "REQUIRED" changes appear first. These changes must be made, or the *cilk2c* compiler will report compile-time errors. Changes marked "SUGGESTED" are merely recommended; generally they describe alternatives to obsolete (but still supported) features of Cilk 1.2.

H.1.1 Major Changes

REQUIRED: remove percent sign delimiters

Cilk 2.0 no longer needs `%%` to delimit Cilk and C code. Cilk thread definitions may now be intermingled with C function definitions, and any occurences of `%%` will be treated as syntax errors.

REQUIRED: remove `type` keyword

Cilk 2.0 can now detect `typedef`ed names without the help of the `type` keyword. It is now illegal to say `type foo`; say `foo` instead.

[1]This chapter was written by Rob Miller.

REQUIRED: add `byvalue` to thread array arguments

For more uniformity with C, Cilk 2.0 requires a special keyword on array arguments that are passed by value. For example:

```
thread foo(int a[5], int b[]);
```

becomes

```
thread foo(byvalue int a[5], byvalue int b[]);
```

REQUIRED: change preprocessor name from *cilkpp* to *cilk2c*

Cilk 2.0 uses a new Cilk-to-C translator, *cilk2c*. If your makefile is based on the examples makefile distributed with Cilk 1.2, make the following change:

```
CILKPP = $(CILK_DIR)/cilkpp/cilkpp
```

becomes

```
CILKPP = $(CILK_DIR)/cilk2c/cilk2c
```

REQUIRED: pass compiler flags to preprocessor

cilk2c runs your Cilk program through the macro preprocessor first, so you must supply it with the include paths (-I...) and defined symbols (-D...) that you would normally give to the C compiler. You can pass *cilk2c* all the flags normally intended for your compiler, if you bracket them with `--` as shown below. If *cilk2c* doesn't understand an argument appearing between `--`, *cilk2c* will silently ignore it.

You should also pass `-link` to *cilk2c*, which causes it to emit a table of thread signatures required by the runtime system. (Warning: `-link` can take optional filename arguments, so make sure that it is followed by either another option or the end of the command line, or it might seize your Cilk source filename as its optional argument.)

If your makefile is based on the examples makefile, simply make the following change:

```
%.c: %.p
$(CILKPP) -o $@ $<
```

becomes

```
%.c: %.cilk
$(CILKPP) -- $(TARGETFLAGS) $(INCDIRS) -- -link -o $@ $<
```

REQUIRED: use typed continuations

Continuations formerly declared like `cont k` should now be declared `cont` *T* `k`, where *T* is any arithmetic type, structure, union, `signal`, or `void`. When you use typed continuations, you can change `Send...Argument` and `Accumulate...` to the primitive statements `send_argument` and `accumulate`, respectively.

Typing your continuations will be mostly straightforward. One subtlety arises in capturing continuations to arrays, as in `?k[exp]`. This expression sets `k` as a continuation to the first element of the array argument, so its type should be the base type of the array. For example:

```
thread foo(int a[]);
cont k;
spawn_next foo(?k[5]);
```

becomes

```
thread foo(byvalue int a[]);
cont int k;
spawn_next foo(?k[5]);
```

Untyped continuations are no longer supported. The compiler will issue a warning.

SUGGESTED: Cilk source files should end in either `.cilk` or `.cilkh`

The filename convention for Cilk 1.2 programs used the extension `.p`, which unfortunately conflicts with the customary extension for Pascal programs. Cilk 2.0 programs should use the extension `.cilk` for source files and `.cilkh` for header files.

No Cilk program file may end with `.c` or `.h`. The Cilk preprocessor interprets such files if they are straight ANSI C code, so Cilk code appearing in them will result in syntax errors. This change may seem odd, but it's necessary. Some Cilk keywords conflict with standard Unix system calls, like `signal`, so attempting to parse standard system header files as if they were Cilk code will result in syntax errors. Rather than requiring the programmer to bracket all system header files with `#pragma lang +C`, *cilk2c* simply assumes every non-Cilk file should be parsed as C.

SUGGESTED: use `send_argument` instead of `SendWordArgument` et al

If you are using typed continuations, you can replace `Send...Argument (k,val)` with `send_argument (k,val)` . The Cilk 1.9 translator will convert `send_argument` into the `Send...Argument` call appropriate to the type of `k`.

Example:

```
cont k;
SendWordArgument(k, 5);
```

becomes

```
cont int k;
send_argument(k, 5);
```

SUGGESTED: use `accumulate` instead of `AccumulateWord` et al

If you are using typed continuations, you can replace `Accumulate...(k, accum_..._op, val)` with `accumulate(k, op, val)`. The Cilk 2.0 translator will convert accumulate into a call to the `Accumulate...` function appropriate to the continuation type, using the appropriate accumulation operator.

Example:

```
cont k;
AccumulateDouble(k, accum_double_mul, 5.0);
```

becomes

```
cont double k;
accumulate(k, mul, 5.0);
```

SUGGESTED: new notation for array continuations and initializers

This change is purely syntactic, motivated by our desire to reserve the `[..]` notation as a `byvalue` array object constructor. The old syntax is obsolete but still supported, with a compiler warning if it is used.

Example:

```
thread foo(int a[10]);
cont x;
int *p;
spawn_next foo(?x[..]);
spawn_next foo(:p[..]);
```

becomes

```
thread foo(byvalue int a[10]);
cont int x;
int *p;
spawn_next foo(?x[]);
spawn_next foo(:p[]);
```

H.1.2 Minor Changes

REQUIRED: remove `globptr`

`Globptr` will be superseded by global shared memory in the next release of Cilk, and is no longer supported in the base language. (For a user implementation of `globptr`, see the `tree.cilk` example.)

REQUIRED: parenthesize processor number in spawn

You must replace `spawn foo(args)@proc` with `spawn foo(args)@(proc)`. This is necessary only if `proc` is a complex expression; if it is simply a constant or variable identifier, parentheses are not necessary.

The motivation for this change is the potential for mistakes when `@proc` is combined with a closure initialization statement. For instance, a programmer might intend to write:

```
spawn foo()@i   /* send closure to processor i... */
  ++j;          /* ...and increment j before posting it */
```

Without the requirement that complex expressions be parenthesized, the processor number expression would capture `++`. As a result, the translator would give this code a completely different interpretation:

```
spawn foo()@i++
   j;
```

REQUIRED: use `# pragma lang +C` to bracket C-only code

If part of the C code in your program uses Cilk reserved words as identifiers, you can avoid syntax errors by bracketing the code with `#pragma lang +C` and `#pragma lang -C`. The code between these pragma directives is lexically scanned as if it were ordinary ANSI C. For example:

```
int thread = 5;
```

becomes

```
#pragma lang +C
int thread = 5;
#pragma lang -C
```

SUGGESTED: use continuation arithmetic instead of `IndexContinuation`

If you are using typed continuations, you can replace `IndexContinuation(k, i, size)` with `k+i`. You can also use assignment operators (`k+=i`) and the increment operators (`k++`, `++k`). Semantics are the same as for pointers.

SUGGESTED: avoid using `ContinuationT` and `cont void`

In addition to the standard arithmetic continuations, you can declare void continuations, like `cont void k`. A void continuation is treated analogously to a void pointer – it is a continuation to an unknown type. Any other type of continuation can be assigned to a void continuation, and vice versa. In fact, untyped continuations like `cont k` are simply interpreted as void continuations.

Void continuations should be regarded as obsolete. The Cilk 2.0 runtime system uses stubs, which require all continuations to be typed.

Certain hackish Cilk codes use the runtime system's continuation type, `ContinuationT`, to store continuations in data structures. Such codes type-check under Cilk 2.0, since `ContinuationT` is treated like a void continuation, but they are likely to break under the stubs version of the runtime system.

Appendix I

People

The Cilk 2.0 development team consisted of the following people:

Robert D. Blumofe
Matteo Frigo
Christopher F. Joerg
Bradley C. Kuszmaul
Charles E. Leiserson
Phil Lisiecki
Howard Lu
Robert Miller
Keith H. Randall
Richard Tauriello
Daricha Techopitayakul
Yuli Zhou

We gratefully acknowledge the contributions of many others, including:

- Michael Halbherr (now of the Boston Consulting Group in Zurich, Switzerland) developed the PCM runtime system, the precursor of Cilk, and many of the design decisions in Cilk are owed to him.
- Arvind of MIT provided support and spiritual guidance throughout the Cilk project.
- Andy Shaw of MIT ported Cilk to the Silicon Graphics Power Challenge SMP.
- John Litvin and Mike Stupak of Intel ported Cilk to the Paragon running under OSF.
- Rolf Riesen of Sandia National Labs ported Cilk to the Intel Paragon MPP.
- Feng Ming Dong of the National University of Singapore ported Cilk to the Sun Sparc SMP. His code is included in this release.

Bibliography

[BB94] Eric A. Brewer and Robert D. Blumofe. Strata: A multi-layer communications library. Technical report, MIT Laboratory for Computer Science, January 1994. To appear. Available from `ftp.lcs.mit.edu` via anonymous ftp, in directory `/pub/supertech/strata`.

[BJK+95] Robert D. Blumofe, Christopher F. Joerg, Bradley C. Kuszmaul, Charles E. Leiserson, Keith H. Randall, and Yuli Zhou. Cilk: An efficient multithreaded runtime system. In *Proceedings of the Fifth ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPoPP) '95*, Santa Barbara, California, July 1995.

[BL93] Robert D. Blumofe and Charles E. Leiserson. Space-efficient scheduling of multithreaded computations. In *Proceedings of the Twenty-Fifth Annual ACM Symposium on the Theory of Computing (STOC '93)*, pages 362–371, San Diego, California, May 1993.

[BL94] Robert D. Blumofe and Charles E. Leiserson. Scheduling multithreaded computations by work-stealing. In *Proceedings of the 35th Annual Symposium on Foundations of Computer Science*, pages 356–368, Santa Fe, New Mexico, November 1994.

[Blu92] Robert D. Blumofe. Managing storage for multithreaded computations. Master's thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, September 1992. Also available as MIT Laboratory for Computer Science Technical Report MIT/LCS/TR-552.

[BP94] Robert D. Blumofe and David S. Park. Scheduling large-scale parallel computations on networks of workstations. In *Proceedings of the Third International Symposium on High-Performance Distributed Computing (HPDC '94)*, pages 96–105, San Francisco, California, August 1994.

[HZJ94a] Michael Halbherr, Yuli Zhou, and Chris F. Joerg. MIMD-style parallel programming based on continuation-passing threads. Computation Structures Group Memo 355, Massachusetts Institute of Technology, Laboratory for Computer Science, 545 Technology Square, Cambridge, MA 02139, April 1994. A shorter version will appear in Proc. of 2nd Int. Workshop on Massive Parallelism: Hardware, Software and Applications. Capri, Italy, Oct. 1994.

[HZJ94b] Michael Halbherr, Yuli Zhou, and Chris F. Joerg. MIMD-style parallel programming based on continuation-passing threads. In *Proc. of 2nd Int. Workshop on Massive Parallelism: Hardware, Software and Applications.*, Capri, Italy, October 1994. To appear.

[JK94] Christopher F. Joerg and Bradley C. Kuszmaul. Massively parallel chess. In *Third DIMACS Parallel Implementation Challenge Workshop*, Rutgers University, October 1994.

[Kus94] Bradley C. Kuszmaul. *Synchronized MIMD Computing.* PhD thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, May 1994.

[LAD+92] Charles E. Leiserson, Zahi S. Abuhamdeh, David C. Douglas, Carl R. Feynman, Mahesh N. Ganmukhi, Jeffrey V. Hill, W. Daniel Hillis, Bradley C. Kuszmaul, Margaret A. St. Pierre, David S. Wells, Monica C. Wong, Shaw-Wen Yang, and Robert Zak. The network architecture of the Connection Machine CM-5. In *Symposium on Parallel Algorithms and Architectures (SPAA '92)*, pages 272–285, San Diego, California, June 1992.

[Mil95] Robert C. Miller. A type-checking preprocessor for Cilk 2, a multithreaded C language. Master's thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, May 1995.

[PJGT] Vijay S. Pande, Chris Joerg, Alexander Yu. Grosberg, and Toyoichi Tanaka. Enumeration of the hamiltonian walks on a cubic sublattice. To appear in Journal of Physics A.