The Synchronous Language Esterel

COMS W4995-02

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The Esterel Language

Developed by Gérard Berry starting 1983

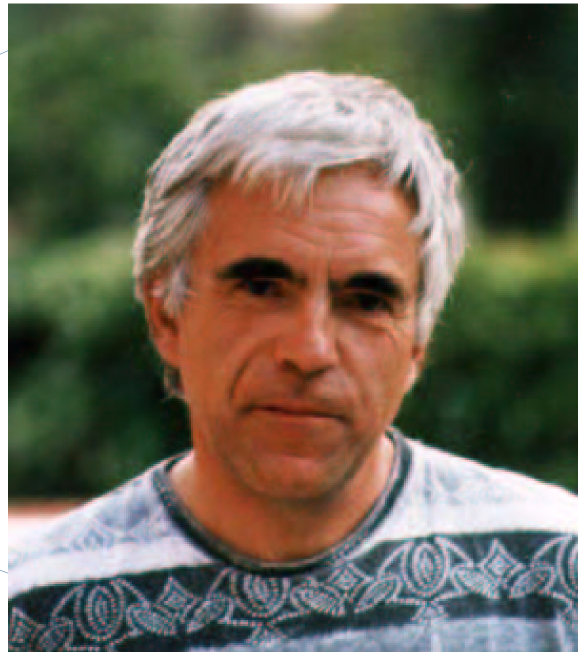
Originally for robotics applications

Imperative, textual language

Synchronous model of time like that in digital circuits

Concurrent

Deterministic

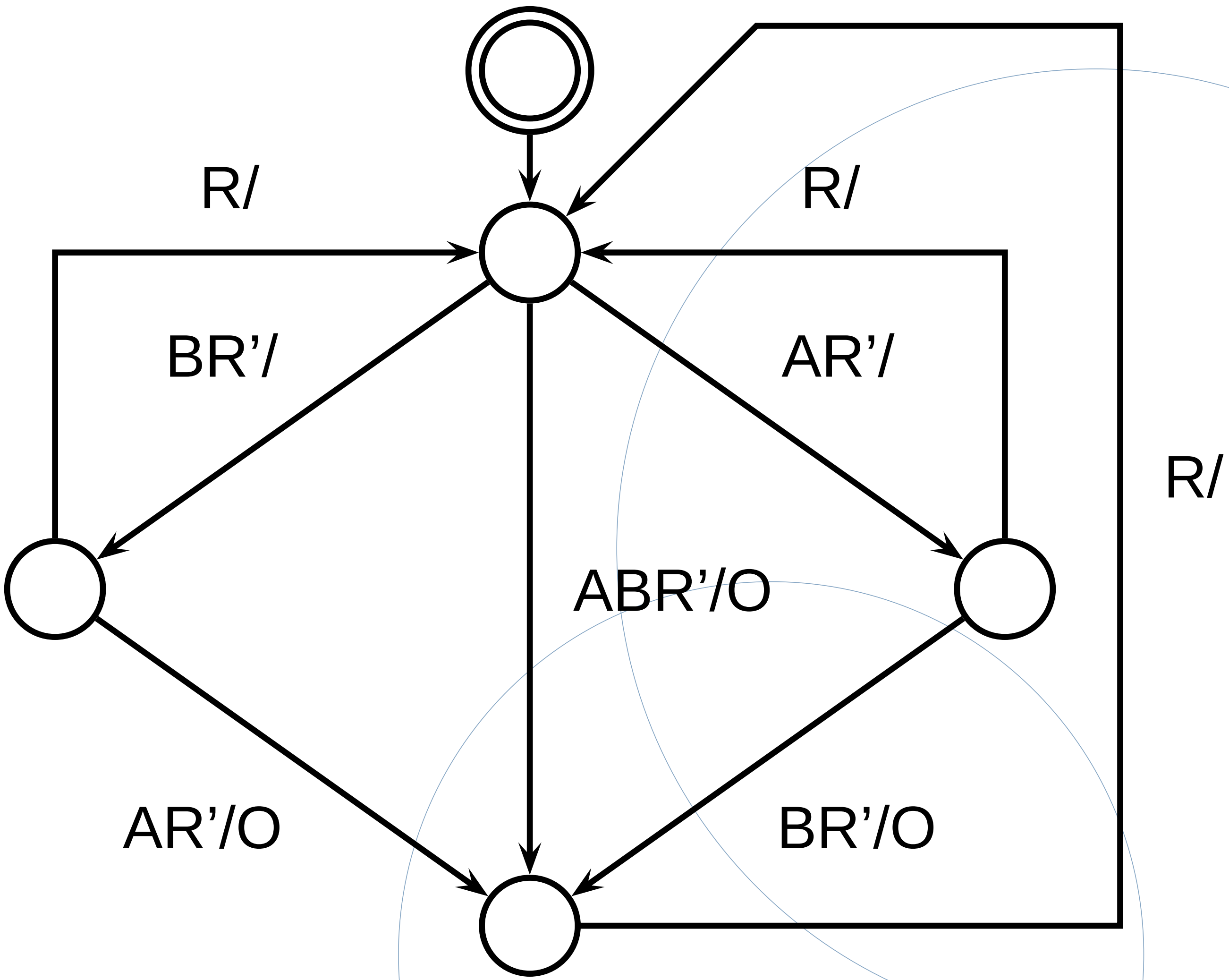


A Simple Example

The specification:

> The output O should occur when inputs A and B have both arrived. The R input should restart this behavior.

A First Try: An FSM



The Esterel Version

```
module ABRO:
input A, B, R;
output O;

loop
  [ await A || await B ];
  emit O
each R

end module
```

Esterel programs built from modules

Each module has an interface of input and output signals

Much simpler since language includes notions of signals, waiting, and reset.

The Esterel Version

```
module ABRO:
input A, B, R;
output O;

loop
  [ await A || await B ];
  emit O
each R

end module
```

loop...each statement implements reset

await waits for the next cycle where its signal is present

|| runs the two awaits in parallel

The Esterel Version

```
module ABRO:
input A, B, R;
output O;

loop
  [ await A || await B ];
  emit O
each R

end module
```

Parallel terminates when all its threads have

Emit O makes signal O present when it runs

Basic Ideas of Esterel

Imperative, textual language

Concurrent

Based on synchronous model of time:

- Program execution synchronized to an external clock
- Like synchronous digital logic
- Suits the cyclic executive approach

Two types of statements:

- Combinational statements, which take “zero time” (execute and terminate in same instant, e.g., emit)
- Sequential statements, which delay one or more cycles (e.g., await)

Uses of Esterel

Wristwatch

- Canonical example
- Reactive, synchronous, hard real-time

Controllers, e.g., for communication protocols

Avionics

- Fuel control system
- Landing gear controller
- Other user interface tasks

Processor components (cache controller, etc.)

Advantages of Esterel

Model of time gives programmer precise timing control

Concurrency convenient for specifying control systems

Completely deterministic

- Guaranteed: no need for locks, semaphores, etc.

Finite-state language

- Easy to analyze
- Execution time predictable
- Much easier to verify formally

Amenable to both hardware and software implementation

Disadvantages of Esterel

Finite-state nature of the language limits flexibility

- No dynamic memory allocation
- No dynamic creation of processes

Little support for handling data; limited to simple decision-dominated controllers

Synchronous model of time can lead to overspecification

Semantic challenges:

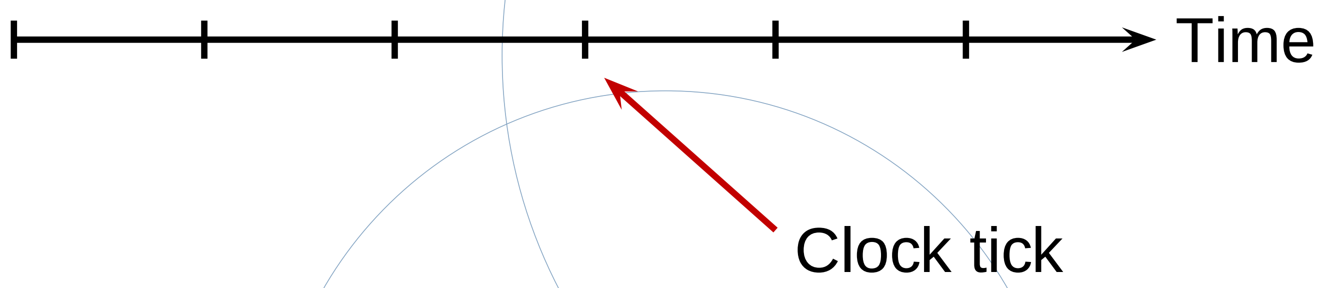
- Avoiding causality violations often difficult
- Difficult to compile

Limited number of users, tools, etc.

Esterel’s Model of Time

The standard CS model (e.g., Java’s) is *asynchronous*: threads run at their own rate. Synchronization is through calls to wait() and notify().

Esterel’s model of time is *synchronous* like that used in hardware. Threads march in lockstep to a **global clock**.



Signals

Esterel programs communicate through signals

These are like wires

Each signal is either present or absent in each cycle

Can’t take multiple values within a cycle

Presence/absence not held between cycles

Broadcast across the program

Any process can read or write a signal

Basic Esterel Statements

`emit` ***S***

Make signal S present in the current cycle

A signal is absent unless emitted *in that cycle*.

`pause`

Stop for this cycle and resume in the next.

`present` ***S*** **`then`** s_1 **`else`** s_2 **`end`**

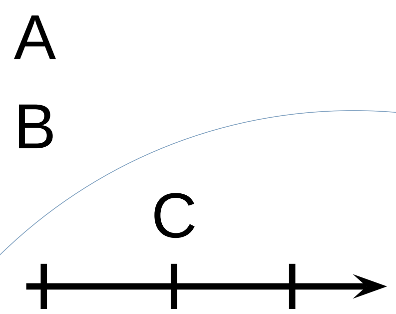
Run s_1 immediately if signal *S* is present in the current cycle, otherwise run s_2

Simple Example

```
module Example1:
output A, B, C;

emit A;
present A then
  emit B
end;
pause;
emit C

end module
```



Signal Coherence Rules

Each signal is only present or absent in a cycle,never both

All writers run before any readers do

Thus

```
present A else
  emit A
end
```

is an erroneous program. (Deadlocks.)

The Esterel compiler rejects this program.

Advantage of Synchrony

Easy to regulate time

Synchronization is free (e.g., no Bakers' algorithm)

Speed of actual computation nearly uncontrollable

Allows function and timing to be specified independently

Makes for deterministic concurrency

Explicit control of "before" "after" "at the same time"

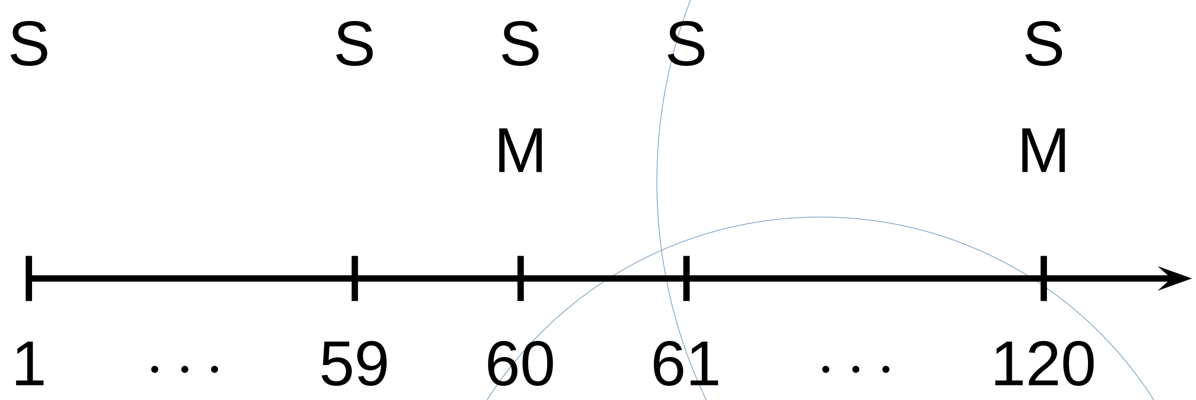
Time Can Be Controlled Precisely

This guarantees every 60th S an M is emitted

```
every 60 S do
  emit M
end
```

`every` invokes its body every 60th S

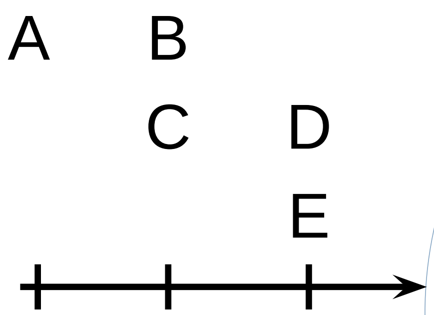
`emit` takes no time (cycles)



The || Operator

Groups of statements separated || by run concurrently and terminate when all groups have terminated

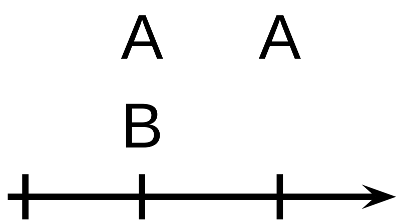
```
[
  emit A; pause; emit B;
||
  pause; emit C; pause; emit D
];
emit E
```



Communication Is Instantaneous

A signal emitted in a cycle is visible immediately

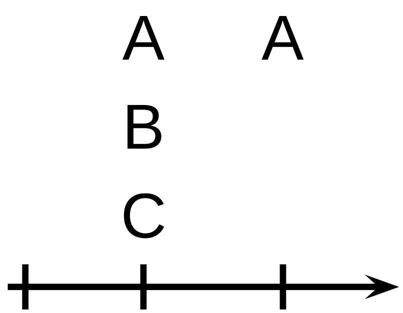
```
[
  pause; emit A; pause; emit A
||
  pause; present A then emit B end
]
```



Bidirectional Communication

Processes can communicate back and forth in the same cycle

```
[
  pause; emit A;
  present B then emit C end;
  pause; emit A
||
  pause; present A then emit B end
]
```



Concurrency and Determinism

Signals are the only way for concurrent processes to communicate

Esterel does have variables, but they cannot be shared

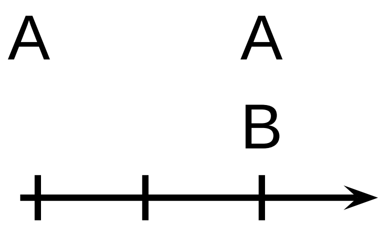
Signal coherence rules ensure deterministic behavior

Language semantics clearly defines who must communicate with whom when

The Await Statement

The await statement waits for a particular cycle await S waits for the next cycle in which S is present

```
[
  emit A ; pause ; pause; emit A
||
  await A; emit B
]
```

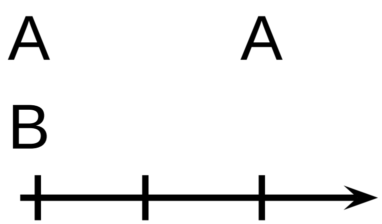


The Await Statement

Await normally waits for a cycle before beginning to check

`await immediate` also checks the initial cycle

```
[
  emit A ; pause ; pause; emit A
||
  await immediate A; emit B
]
```



Loops

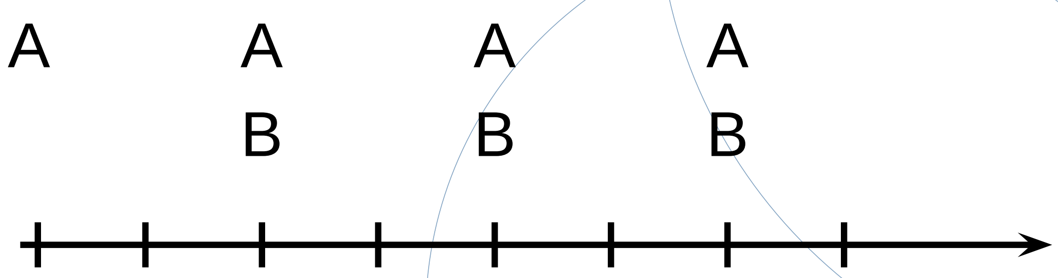
Esterel has an infinite loop statement

Rule: loop body cannot terminate instantly

Needs at least one pause, await, etc.

Can't do an infinite amount of work in a single cycle

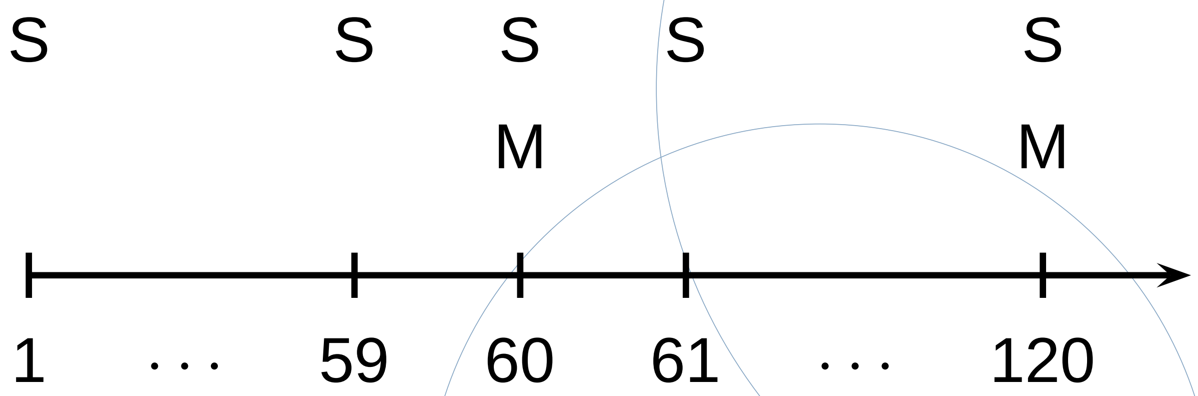
```
loop
  emit A; pause; pause; emit B
end
```



Loops and Synchronization

Instantaneous nature of loops plus await provide very powerful synchronization mechanisms

```
loop
   await 60 S;
   emit M
end
```



Preemption

Often want to stop doing something and start doing something else

E.g., Ctrl-C in Unix: stop the currently-running program

Esterel has many constructs for handling preemption

The Abort Statement

Basic preemption mechanism

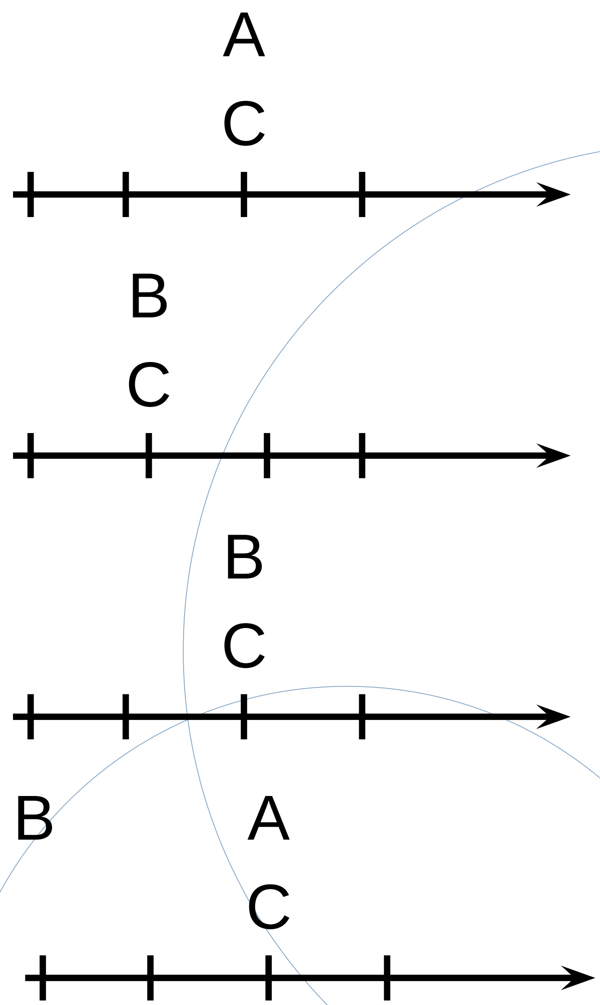
General form:

`abort`
    statement
`when` *condition*

Runs *statement* to completion. If *condition* ever holds, **`abort`** terminates immediately.

The Abort Statement

```
abort
  pause;
  pause;
  emit A
when B;
emit C
```



Normal Termination

Aborted termination

Aborted termination;
emit A preempted

Normal Termination
B not checked
in first cycle
(like await)

Strong vs. Weak Preemption

Strong preemption:

- The body does not run when the preemption conditionholds
- The previous example illustrated strong preemption

Weak preemption:

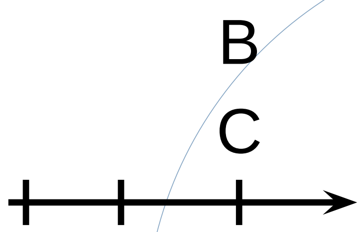
- The body is allowed to run even when the preemptioncondition holds, but is terminated thereafter
- “weak abort” implements this in Esterel

Strong vs. Weak Abort

Strong abort

emit A does not run

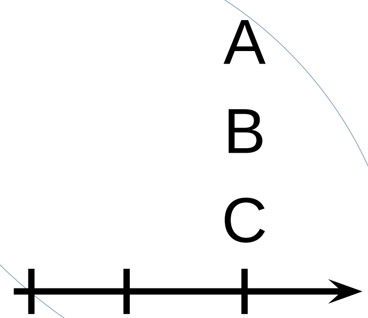
```
abort
  pause;
  pause;
  emit A;
  pause
when B;
emit C
```



Weak abort

emit A runs

```
weak abort
  pause;
  pause;
  emit A;
  pause
when B;
emit C
```



Strong vs. Weak Preemption

Important distinction

Something may not cause its own strong preemption

Erroneous

```
abort
  pause; emit A
when A
```

OK

```
weak abort
  pause; emit A
when A
```

The Trap Statement

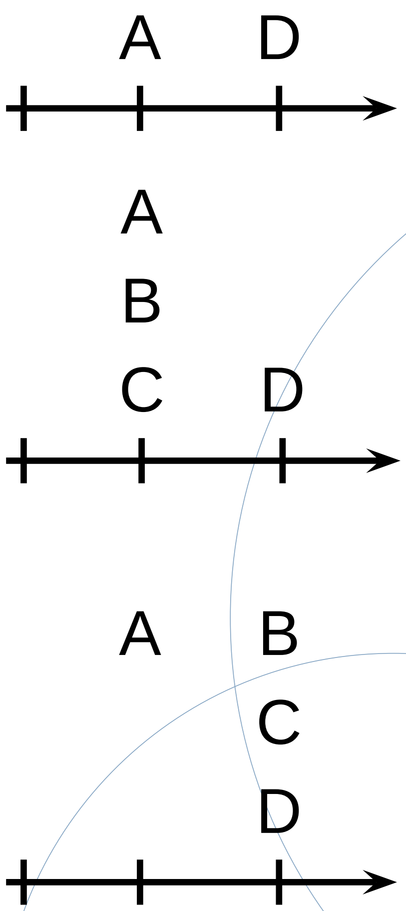
Esterel provides an exception facility for weak preemption

Interacts nicely with concurrency

Rule: outermost trap takes precedence

The Trap Statement

```
trap T in
[
  pause;
  emit A;
  pause;
  exit T
||
  await B;
  emit C
]
end trap;
emit D
```



Normal termination from first process

Emit C also runs

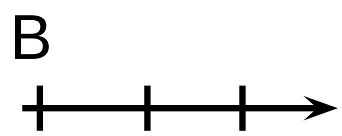
Second process allowed to run even though first process has exited

Nested Traps

```
trap T1 in
  trap T2 in
  [
    exit T1
  ||
    exit T2
  ]
  end;
  emit A
end;
emit B
```

Outer trap takes precedence; control transferred directly to the outer trap statement.

`emit A` not allowed to run.



The Suspend Statement

Preemption (abort, trap) terminate something, but what if you want to resume it later?

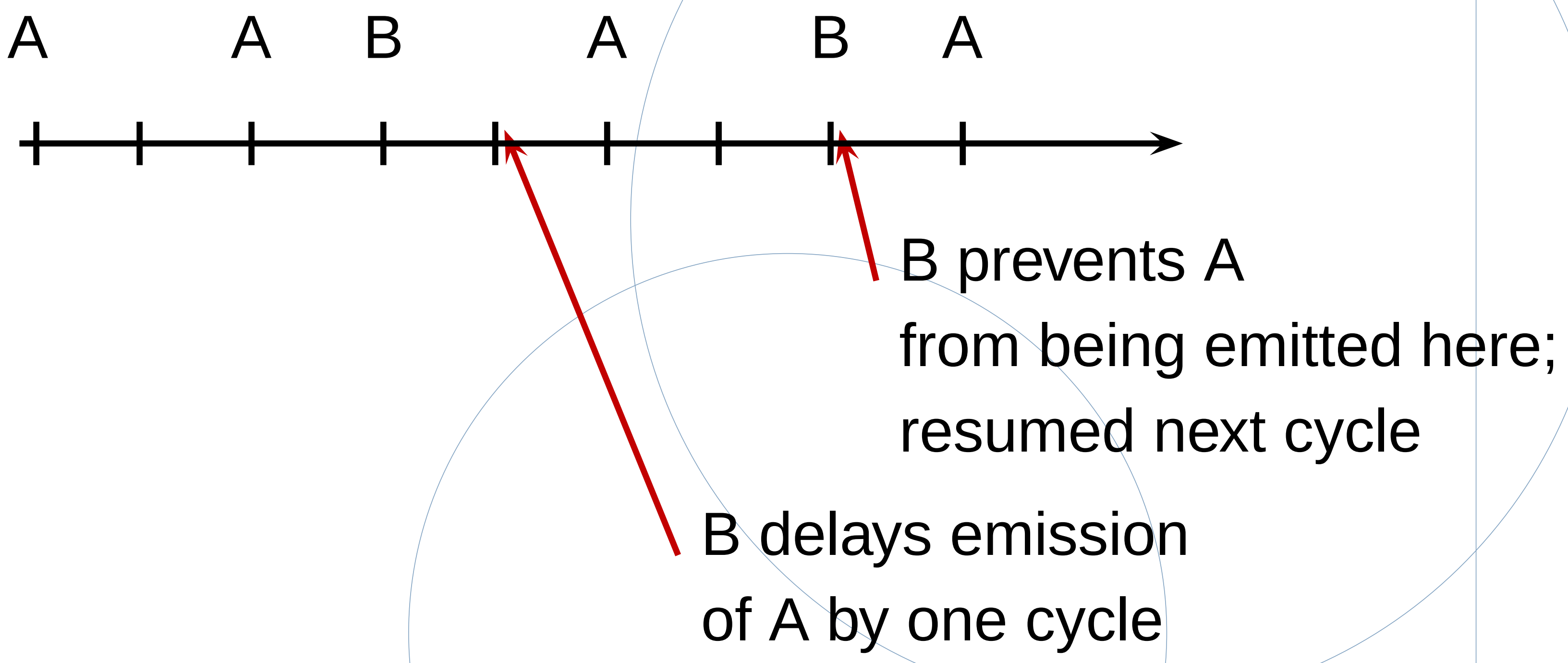
Like the unix Ctrl-Z

Esterel's suspend statement pauses the execution of a group of statements

Only strong preemption: statement does not run when condition holds

The Suspend Statement

```
suspend
  loop
    emit A; pause; pause
  end
when B
```



Causality

Unfortunate side-effect of instantaneous communication coupled with the single valued signal rule

Easy to write contradictory programs, e.g.,

```
present A else emit A end

abort pause; emit A when A

present A then nothing end; emit A
```

These sorts of programs are erroneous; the Esterel compiler refuses to compile them.

Causality

Can be very complicated because of instantaneous communication

For example, this is also erroneous

```
  abort
    pause;
    emit B
  when A
||
  pause;
  present B then emit A end
```

Emission of B indirectly causes emission of A

Causality

Definition has evolved since first version of the language

Original compiler had concept of “potentials”

Static concept: at a particular program point, which signals could be emitted along any path from that point

Latest definition based on “constructive causality”

Dynamic concept: whether there’s a “guess-free proof” that concludes a signal is absent

Causality Example

```
emit A;
present B then emit C end;
present A else emit B end;
```

Red statements reachable

Considered erroneous under the original compiler

After emit A runs, there's a static path to emit B Therefore, the value of B cannot be decided yet

Execution procedure deadlocks: program is bad

Causality Example

```
emit A;
present B then emit C end;
present A else emit B end;
```

Red statements reachable

Considered acceptable to the latest compiler

After emit A runs, it is clear that B cannot be emitted because A's presence runs the "then" branch of the second present

B declared absent, both present statements run

Compiling Esterel

Semantics of the language are formally defined and deterministic

It is the responsibility of the compiler to ensure the generated executable behaves correctly w.r.t. the semantics

Challenging for Esterel

Compilation Challenges

- Concurrency
- Interaction between exceptions and concurrency
- Preemption
- Resumption (pause, await, etc.)
- Checking causality
- Reincarnation

  Loop restriction prevents most statements from executing more than once in a cycle

  Complex interaction between concurrency, traps, and loops allows certain statements to execute twice or more

Automata-Based Compilation

Key insight: Esterel is a finite-state language

Each state is a set of program counter values where the program has paused between cycles

Signals are not part of these states because they do not hold their values between cycles

Esterel has variables, but these are not considered part of the state

Automata Compiler Example

```
loop
  emit A;
  await C;
  emit B;
  pause
end
```

```
void tick() {
  static int s = 0;
  A = B = 0;

  switch (s) {
  case 0:
     A = 1;
     s = 1;
     break;
  case 1:
     if (C) {
       B = 1; s = 0;
     }
     break;
  }
}
```

Automata Compiler Example

```
emit A;
emit B;
await C;
emit D;
present E then
   emit B
end
```

```
switch (s) {
case 0:
   A=1;
   B=1;
   s=1;
   break;
case 1:
  if (C) {
    D=1;
    if (E) B=1;
    s=2;
  }
  break;
case 2:
}
```

Automata Compilation Considered

Very fast code (Internal signaling can be compiled away)

Can generate a lot of code because concurrency can cause exponential state growth

n-state machine interacting with another n-state machine can produce n^2 states

Language provides input constraints for reducing states

- “these inputs are mutually exclusive”

  ```
  relation A # B # C;
  ```

- “if this input arrives, this one does, too”

  ```
  relation D => E;
  ```

Automata Compilation

Not practical for large programs

Theoretically interesting, but don't work for most programs longer than 1000 lines

All other techniques produce slower code

Netlist-Based Compilation

Key insight: Esterel programs can be translated into Boolean logic circuits

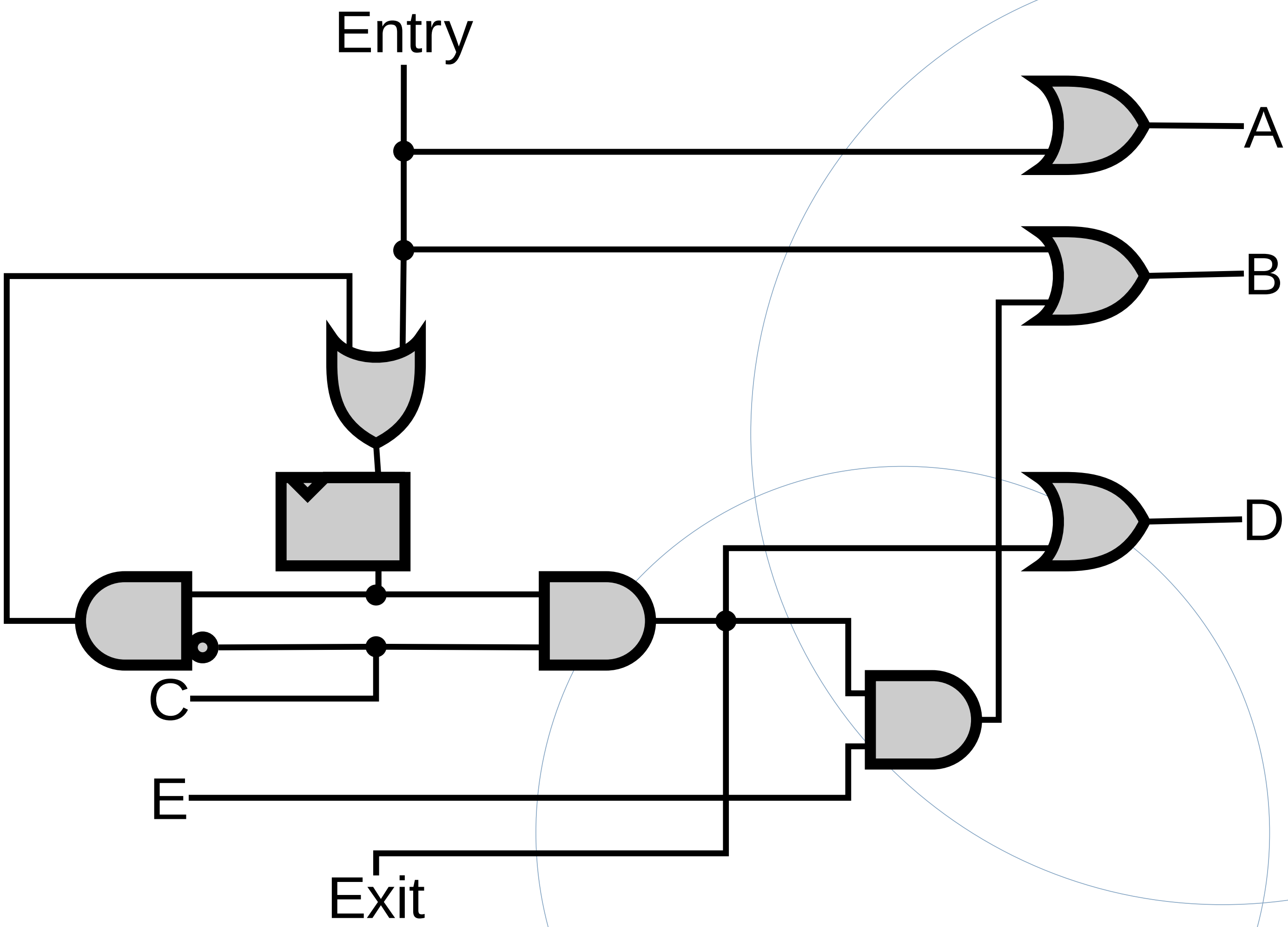
Netlist-based compiler:

Translate each statement into a small number of logic gates, a straightforward, mechanical process

Generate code that simulates the netlist

Netlist Example

```
emit A; emit B; await C;
emit D; present E then emit B end
```



Netlist Compilation Considered

Scales very well

- Netlist generation roughly linear in program size
- Generated code roughly linear in program size

Good framework for analyzing causality

- Semantics of netlists straightforward
- Constructive reasoning equivalent to three-valued simulation

Terribly inefficient code

- Lots of time wasted computing irrelevant values
- Can be hundreds of time slower than automata
- Little use of conditionals

Netlist Compilation

Currently the only solution for large programs that appear to have causality problems

Scalability attractive for industrial users

Currently the most widely-used technique

Control-Flow Graph-Based

Key insight: Esterel looks like a imperative language, so treat it as such

Esterel has a fairly natural translation into a concurrent control-flow graph

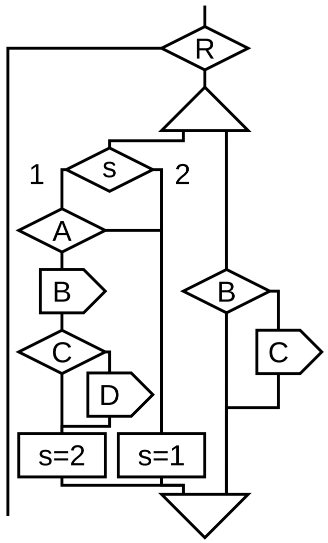
Trick is simulating the concurrency

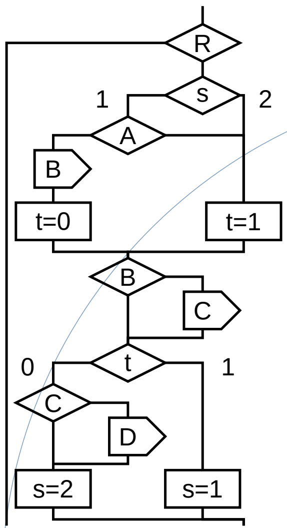
Concurrent instructions in most Esterel programs can be scheduled statically

Use this schedule to build code with explicit context switches in it

Overview

```
every R do
   loop
      await A;
      emit B;
      present C then
         emit D end;
      pause
   end
||
   loop
      present B then
         emit C end;
      pause
   end
end
```



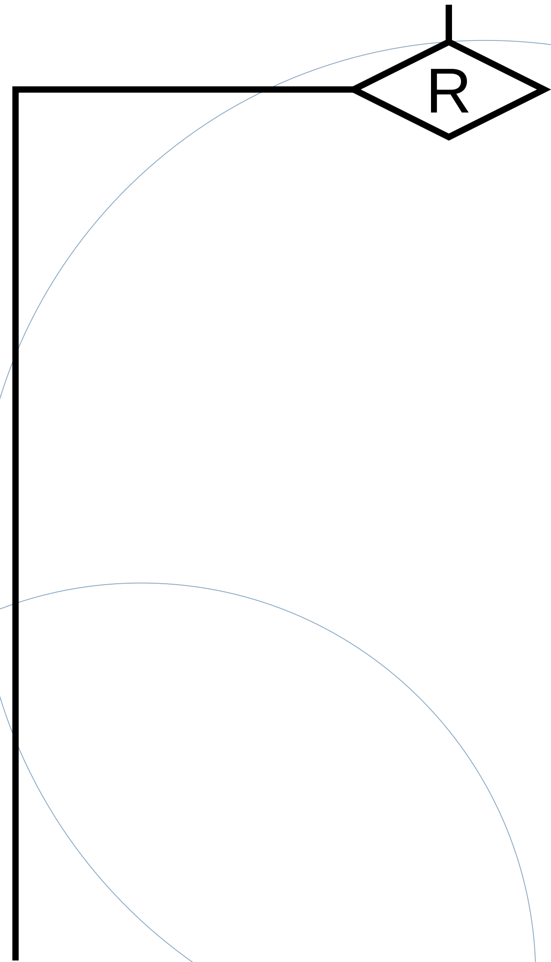



```
if ((s0 & 3) == 1) {
  if (S) {
    s3 = 1; s2 = 1; s1 = 1;
  } else
    if (s1 >> 1)
      s1 = 3;
    else {
      if ((s3 & 3) == 1) {
         s3 = 2; t3 = L1;
      } else {
         t3 = L2;
      }
```

Esterel Source | Concurrent CFG | Sequential CFG | C code

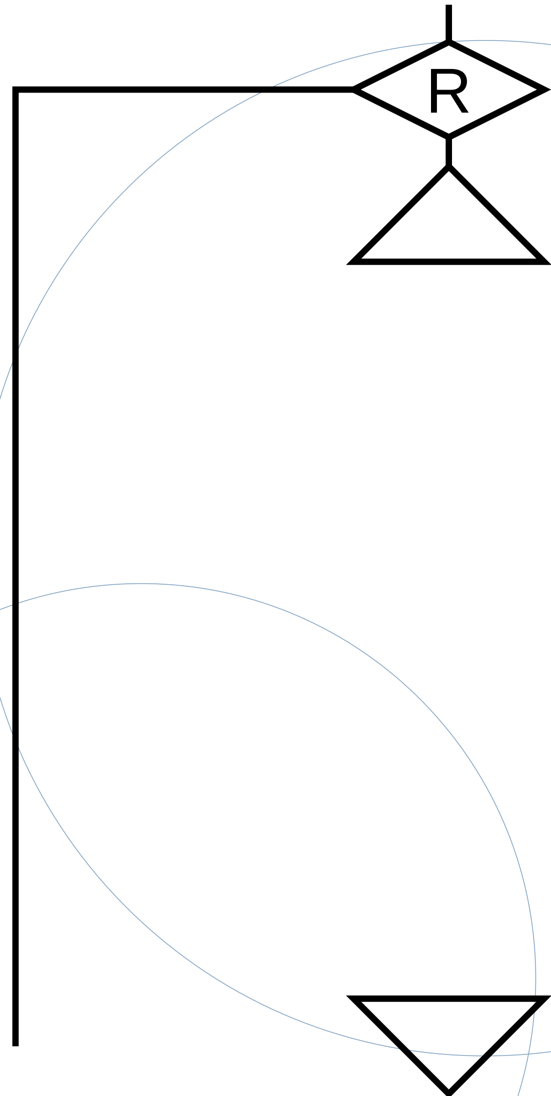
Translate every

```
every R do
   loop
      await A;
      emit B;
      present C then
         emit D end;
      pause
   end
||
   loop
      present B then
         emit C end;
      pause
   end
end
```



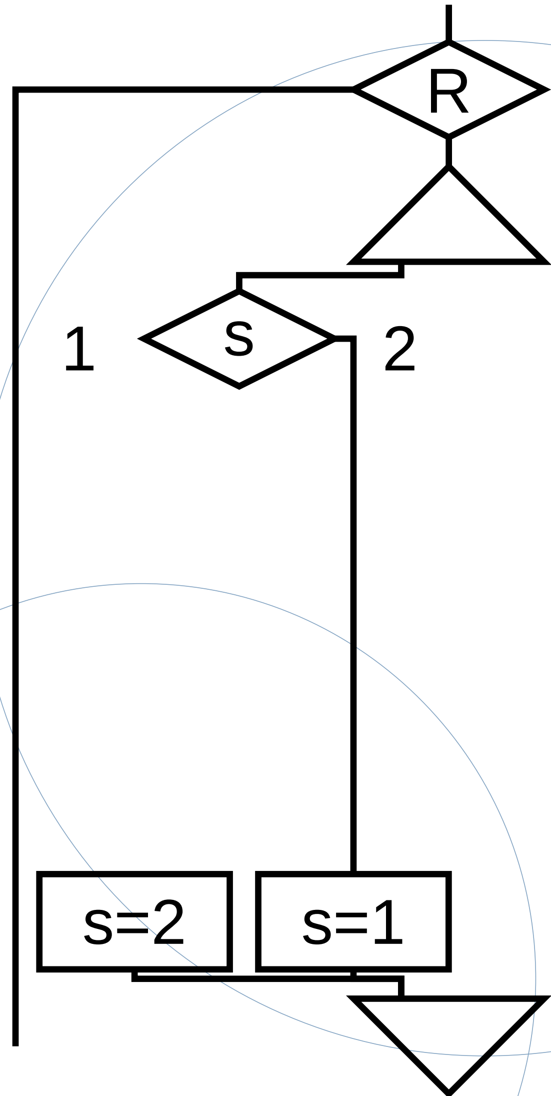
Add Threads

```
every R do
    loop
        await A;
        emit B;
        present C then
            emit D end;
        pause
    end
||
    loop
        present B then
            emit C end;
        pause
    end
end
```



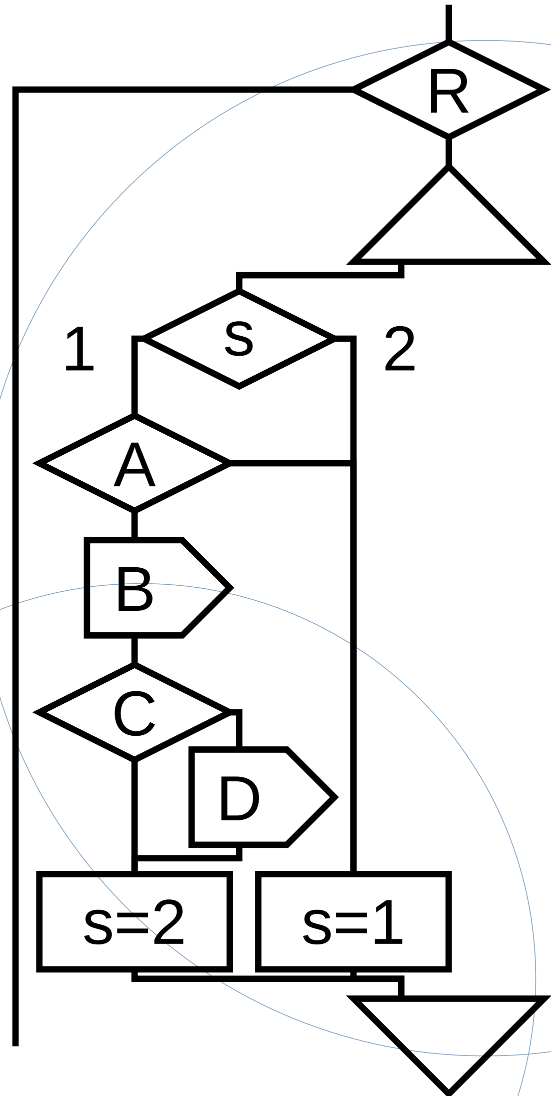
Split at Pauses

```
every R do
  loop
    await A;
    emit B;
    present C then
      emit D end;
    pause
  end
||
  loop
    present B then
      emit C end;
    pause
  end
end
```



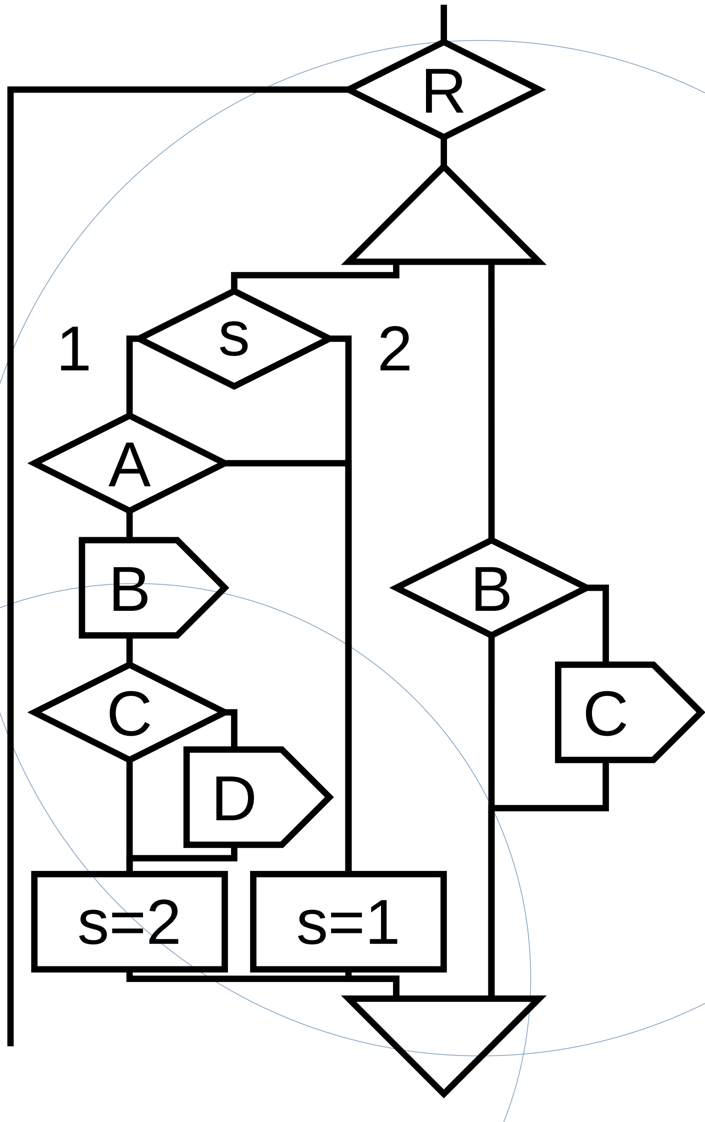
Add Code Between Pauses

```
every R do
  loop
    await A;
    emit B;
    present C then
      emit D end;
    pause
  end
||
  loop
    present B then
      emit C end;
    pause
  end
end
```



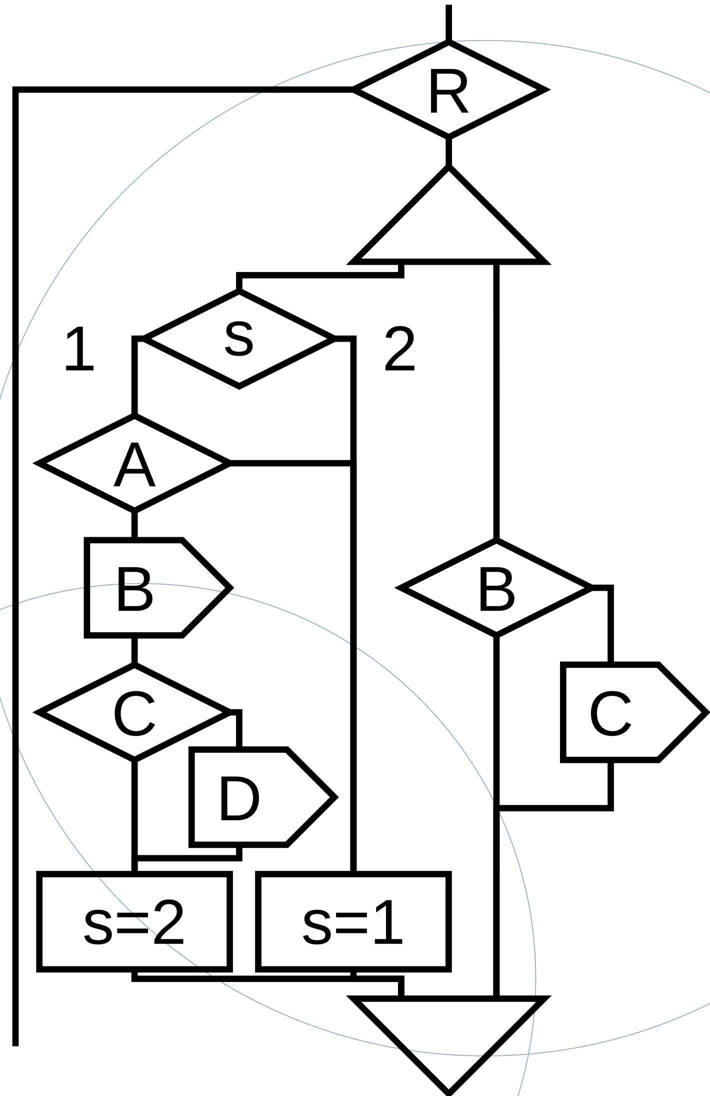
Translate Second Thread

```
every R do
  loop
    await A;
    emit B;
    present C then
      emit D end;
    pause
  end
||
  loop
    present B then
      emit C end;
    pause
  end
end
```



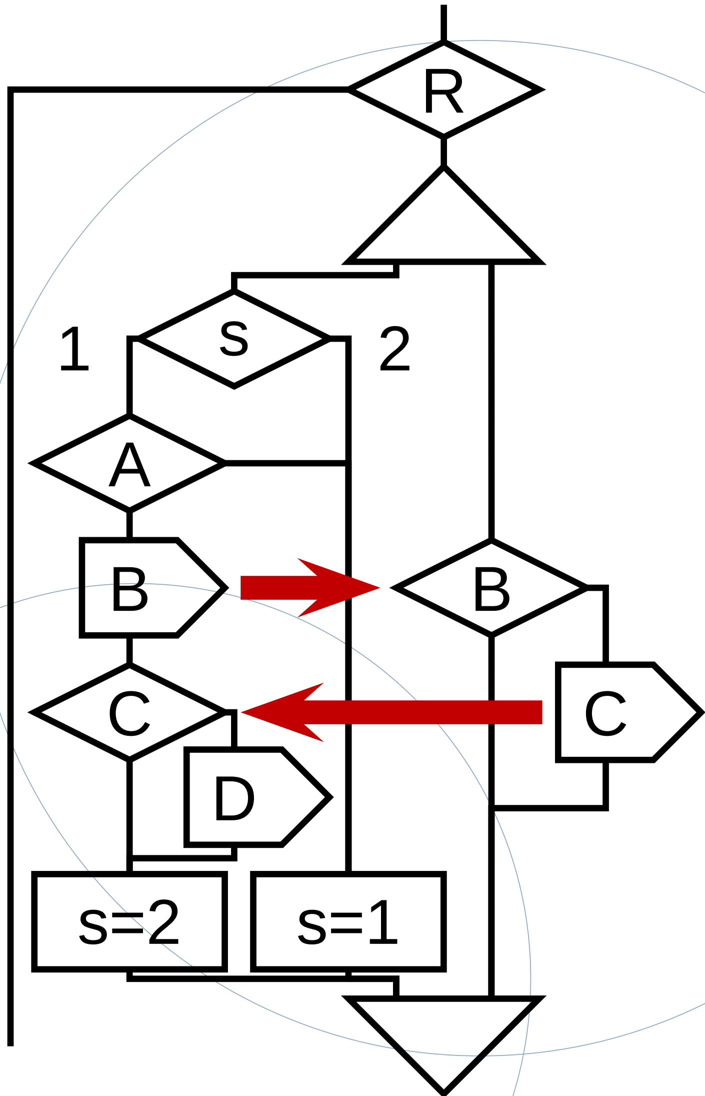
Finished Translating

```
every R do
   loop
      await A;
      emit B;
      present C then
         emit D end;
      pause
   end
||
   loop
      present B then
         emit C end;
      pause
   end
end
```

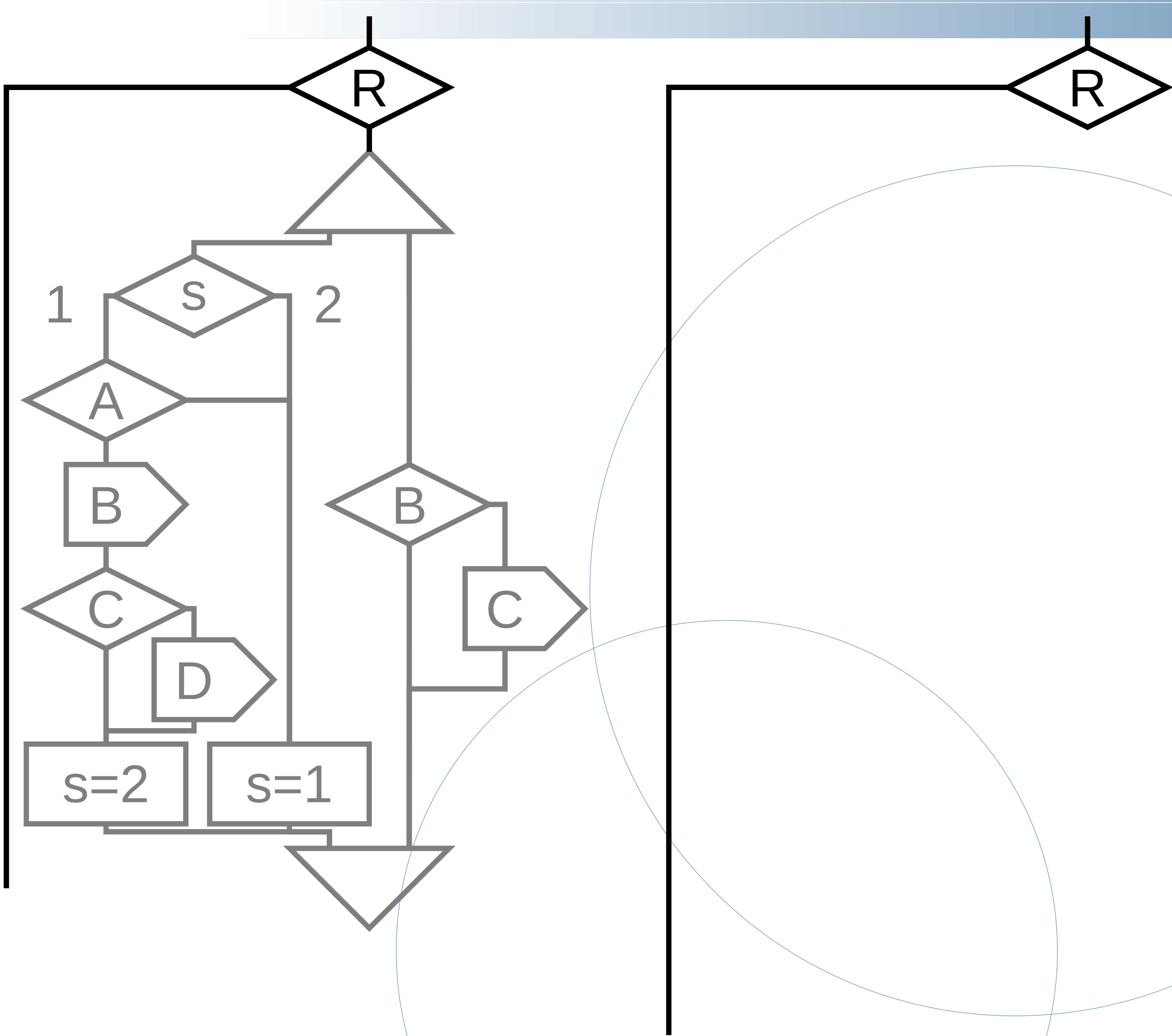


Add Dependencies and Schedule

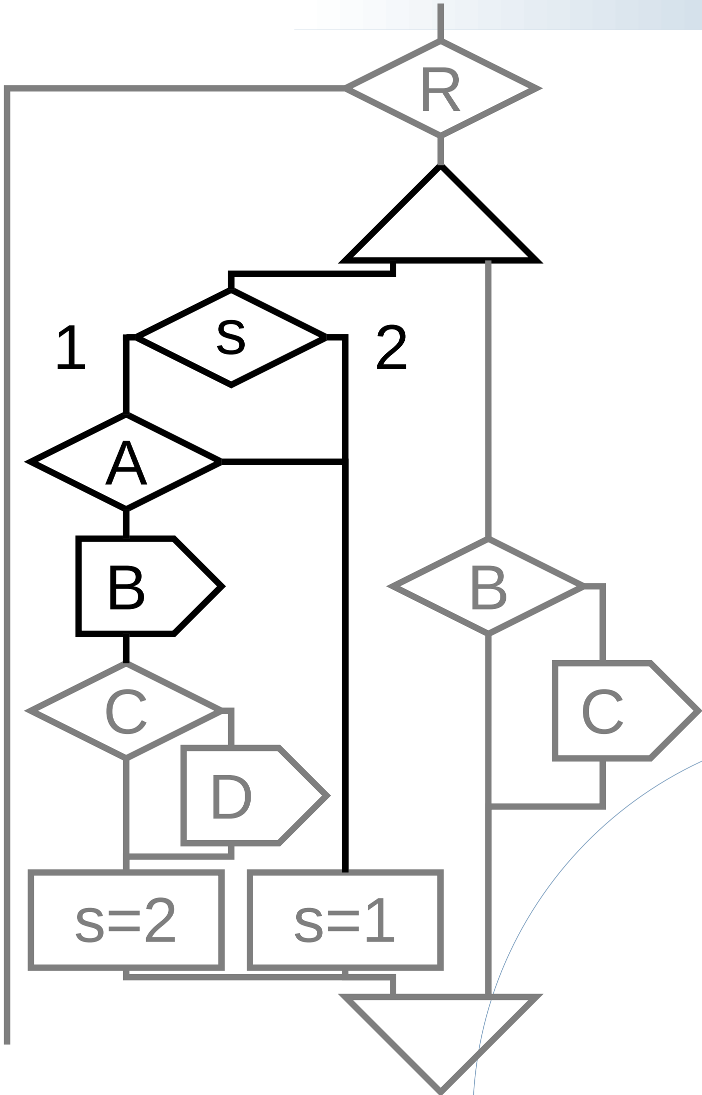
```
every R do
   loop
      await A;
      emit B;
      present C then
         emit D end;
      pause
   end
||
   loop
      present B then
         emit C end;
      pause
   end
end
```

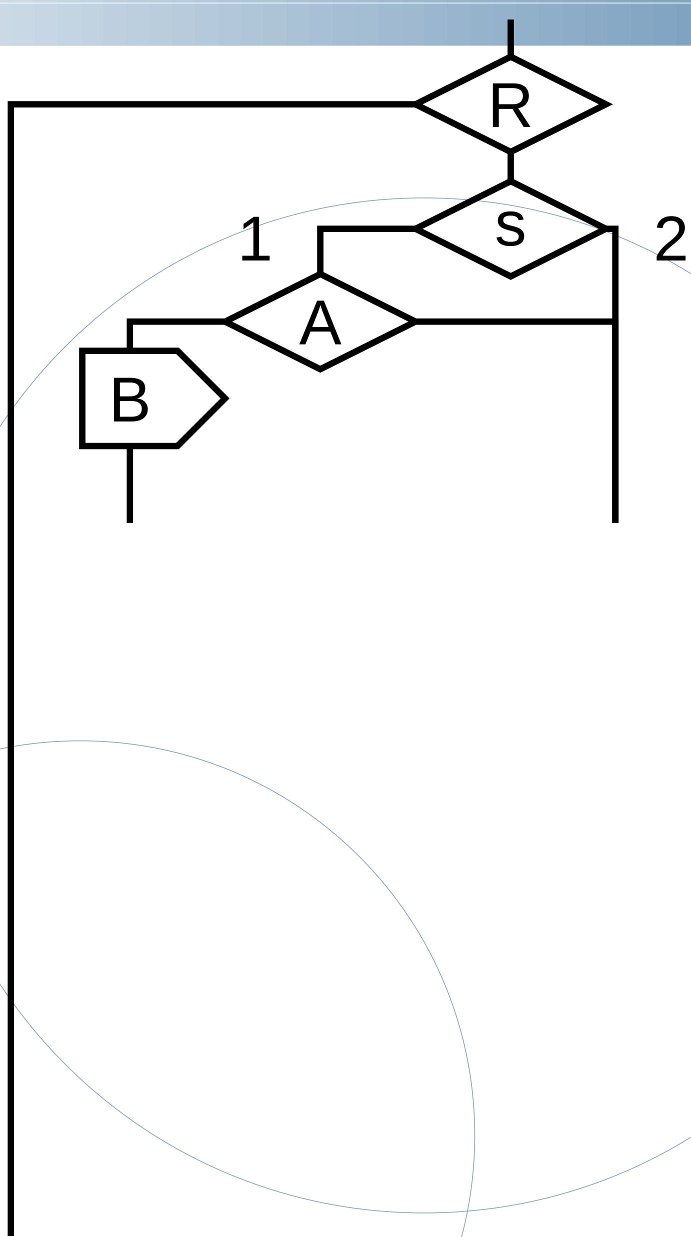


Run First Node

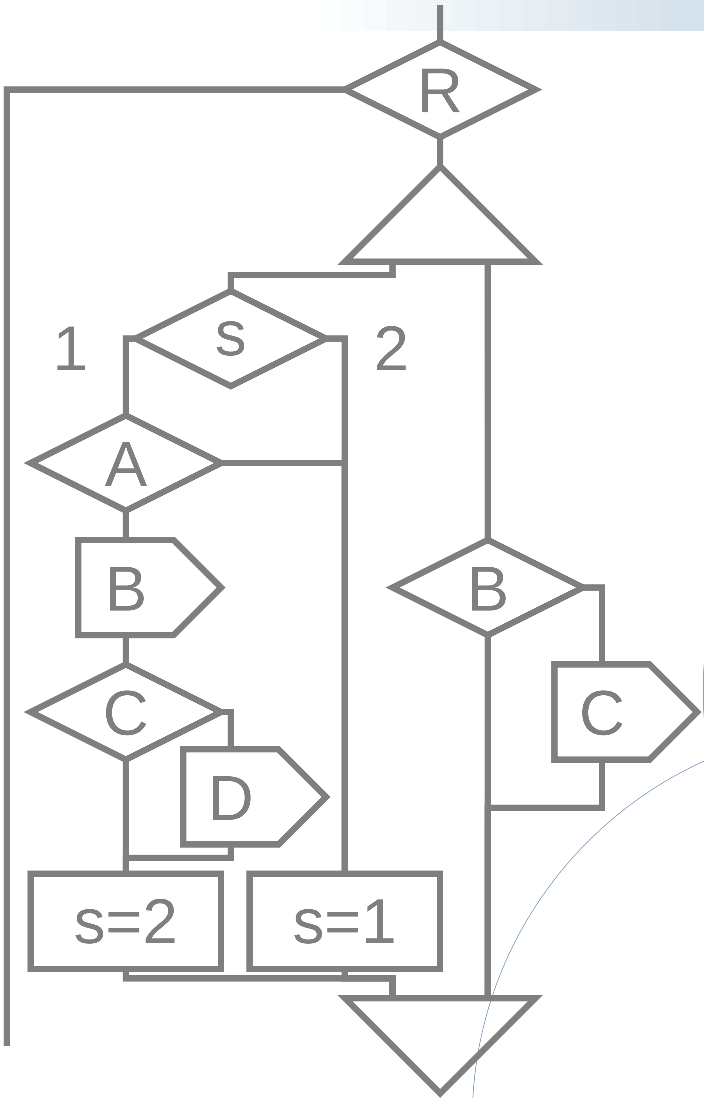


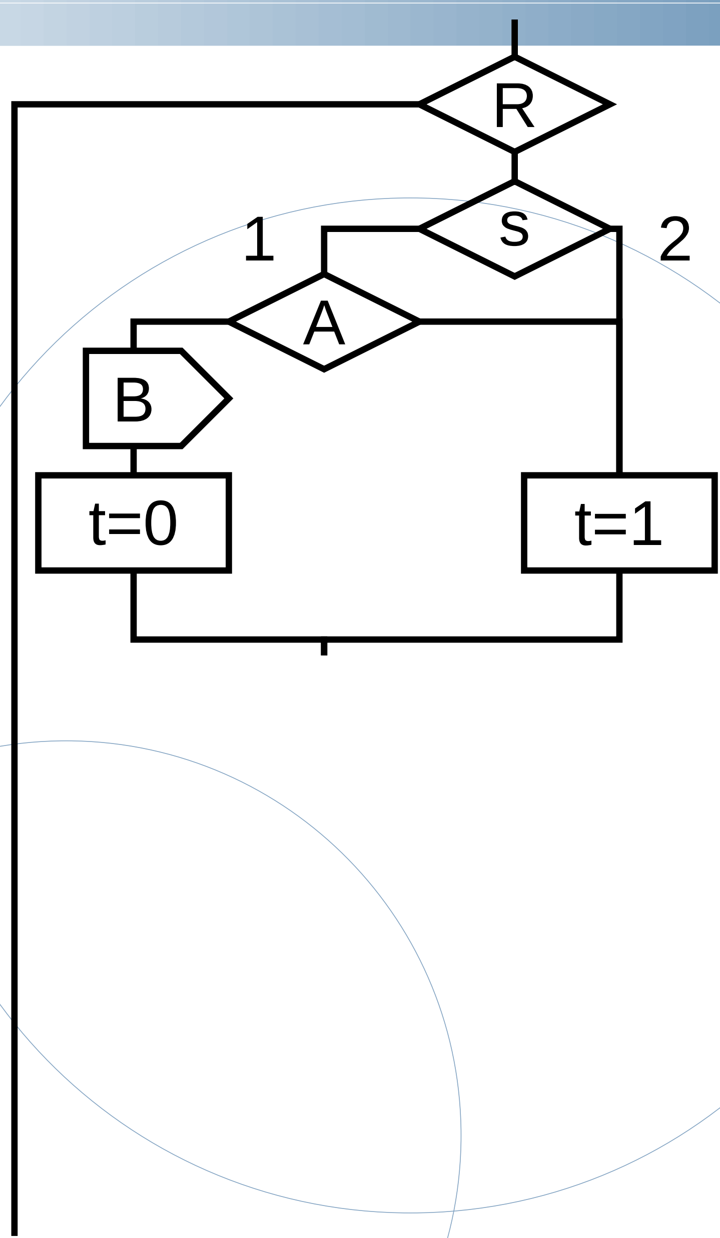
Run First Part of Left Thread



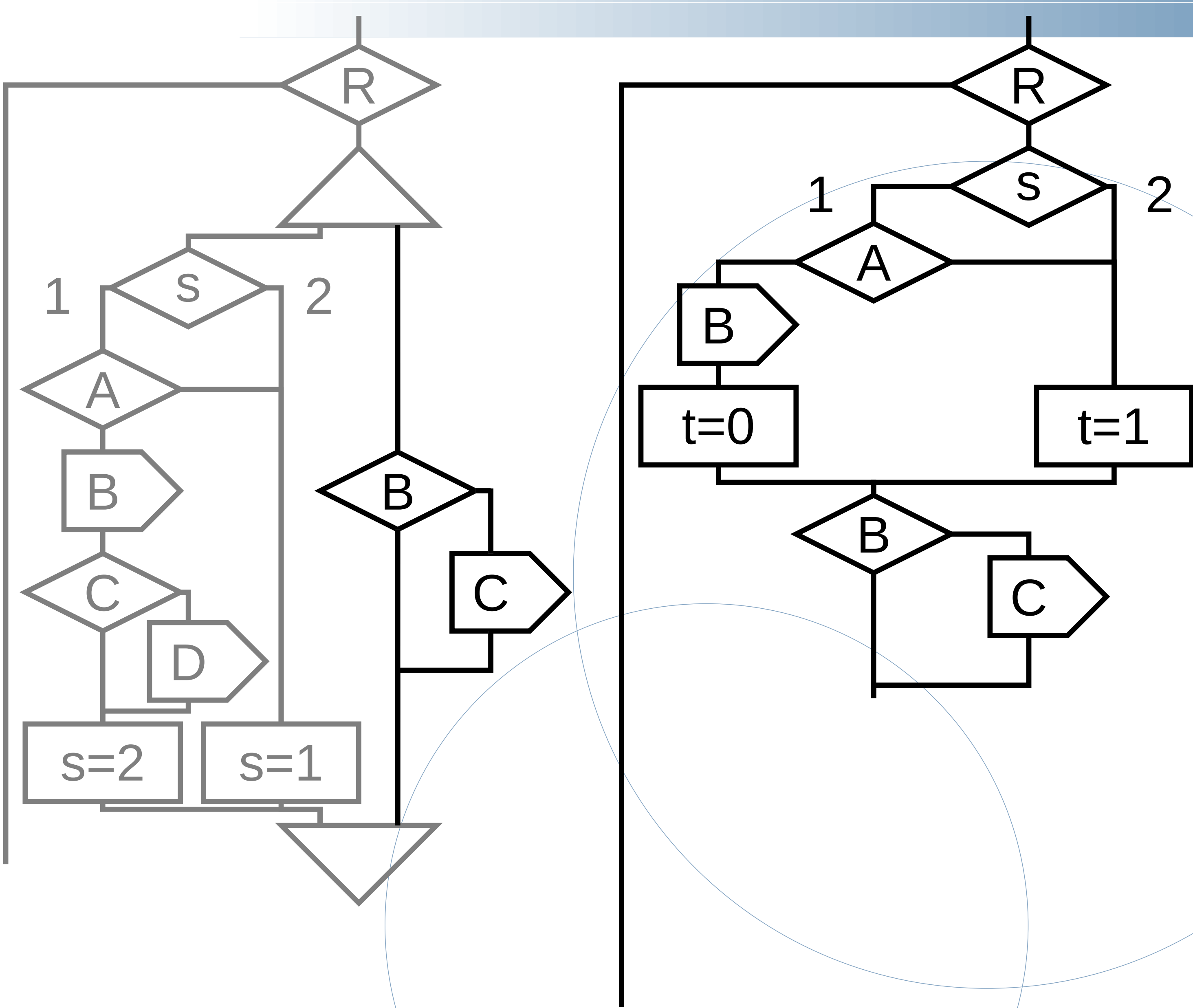


Context Switch

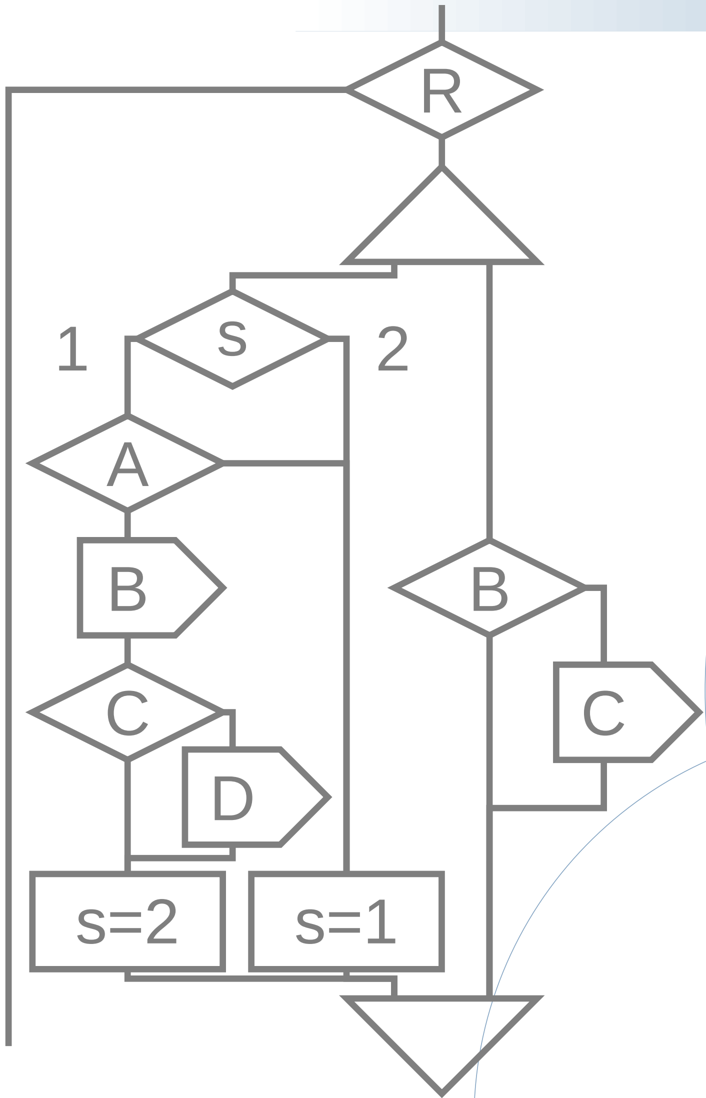


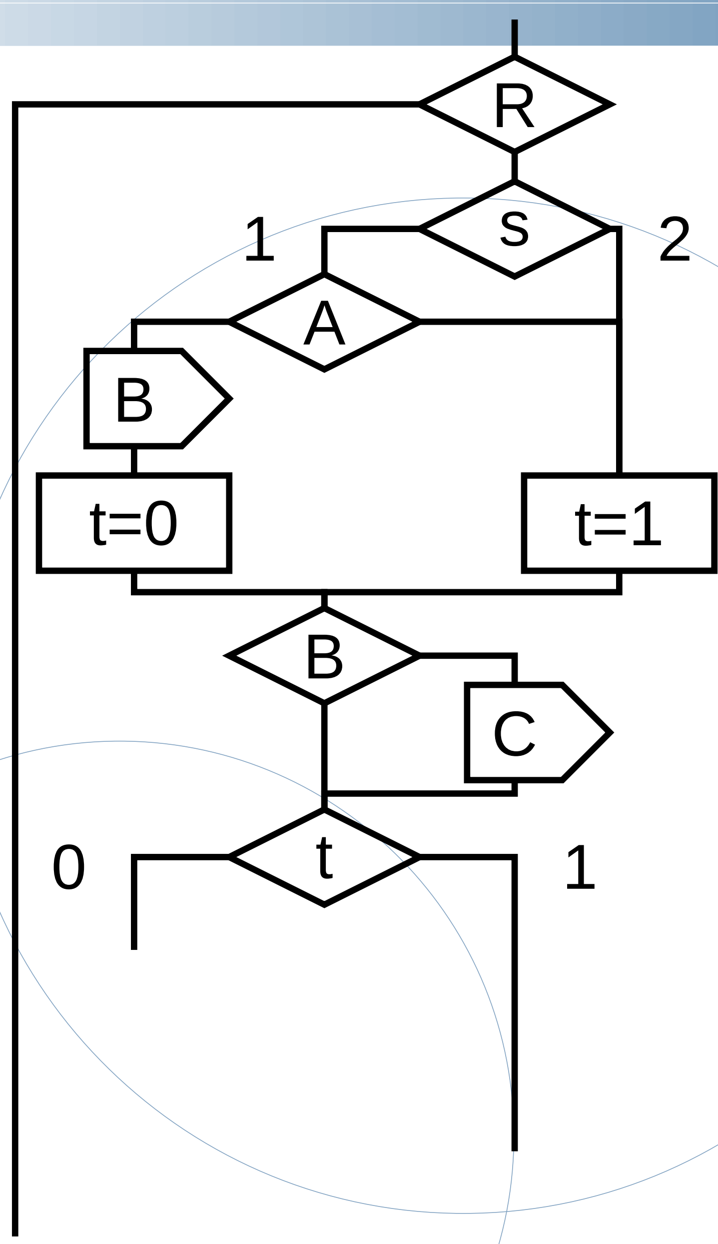


Run Right Thread

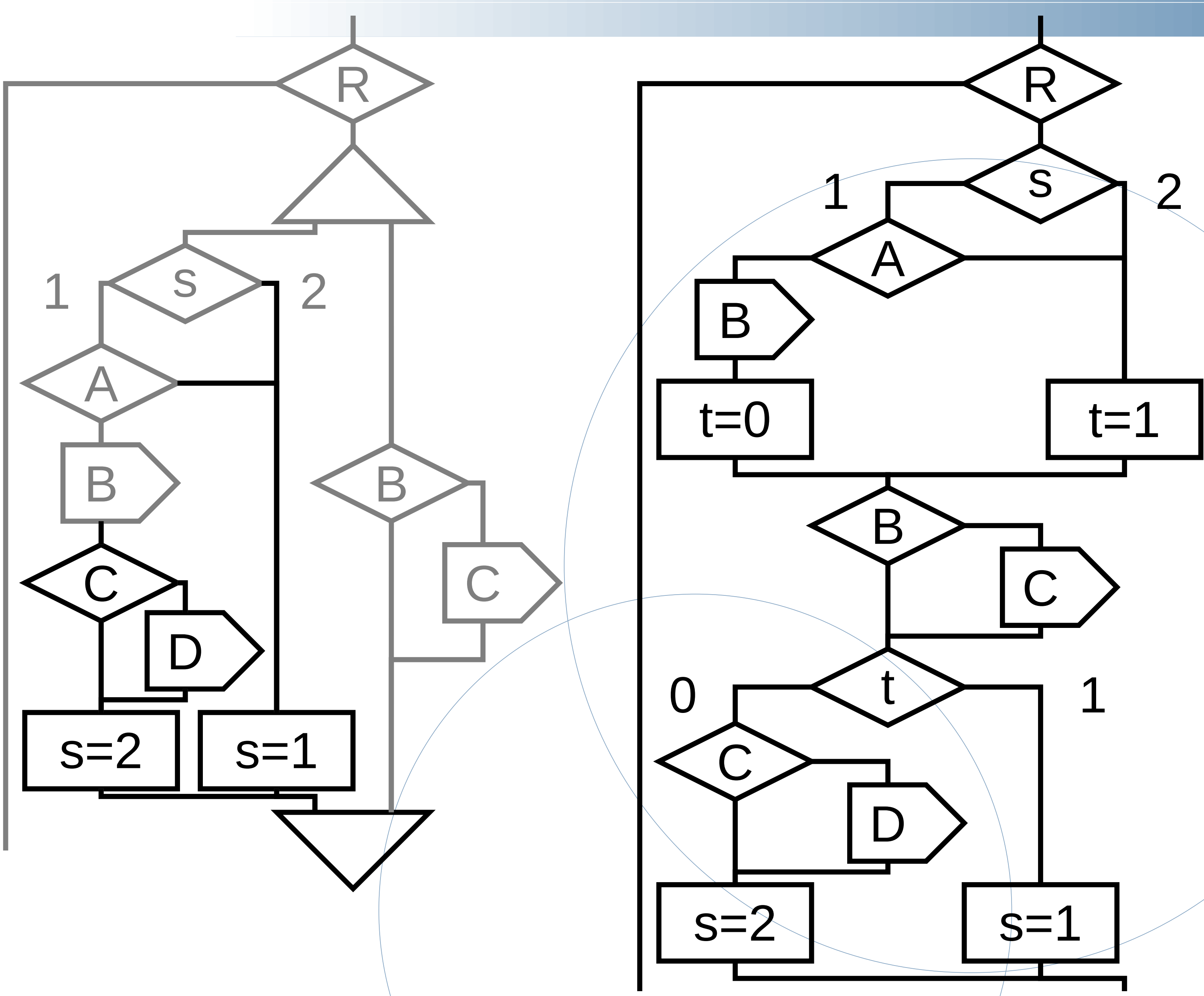


Context Switch

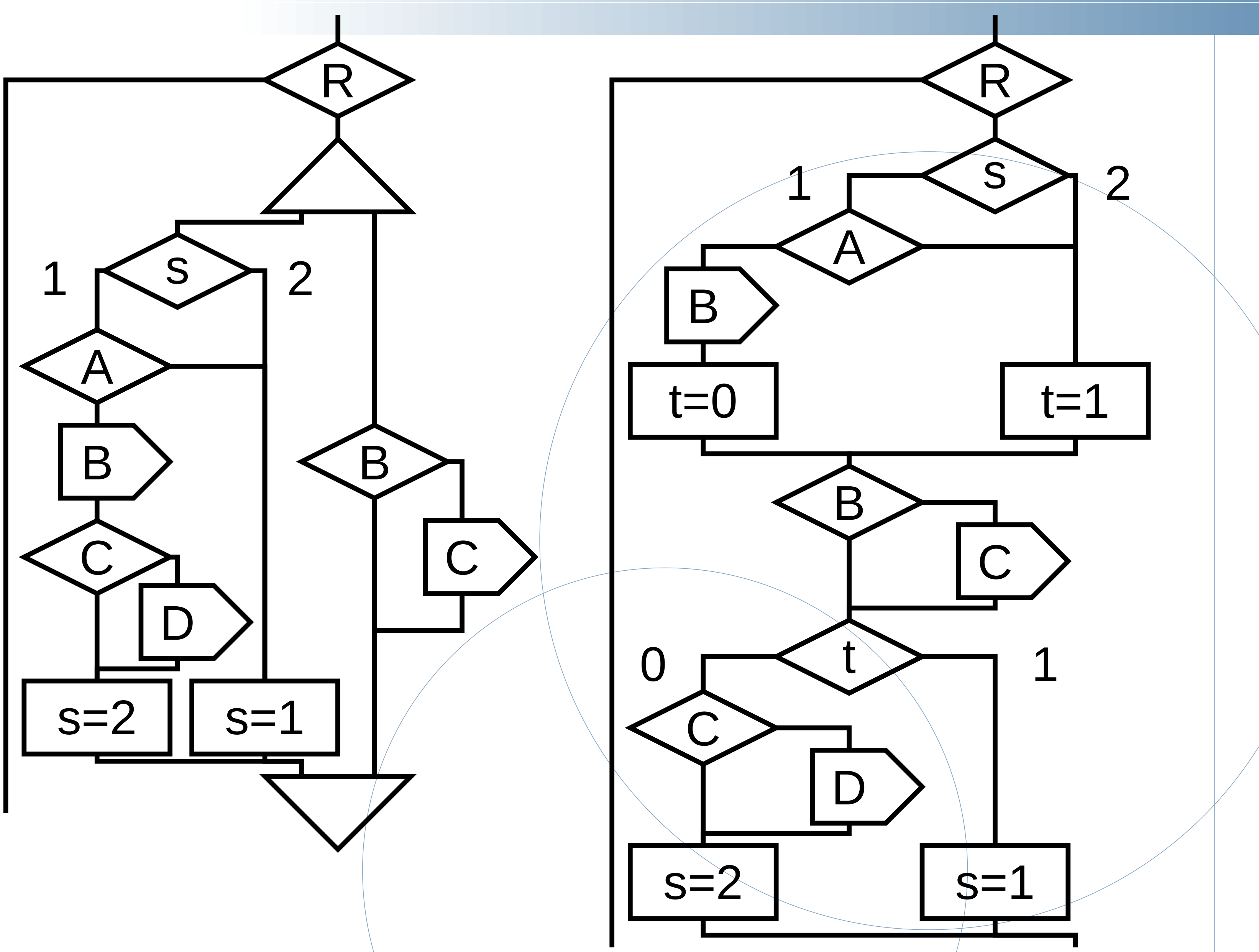




Finish Left Thread



Completed Example



Control-flow Approach Considered

Scales as well as the netlist compiler, but produces much faster code, almost as fast as automata

Not an easy framework for checking causality

Static scheduling requirement more restrictive than netlist compiler

This compiler rejects some programs the others accept

Only implementation hiding within Synopsys' CoCentric System Studio. Will probably never be used industrially.

See my recent IEEE Transactions on Computer-Aided Design paper for details

What To Understand About Esterel

Synchronous model of time

- Time divided into sequence of discrete instants
- Instructions either run and terminate in the sameinstant or explicitly in later instants

Idea of signals and broadcast

- “Variables” that take exactly one value each instant and don’t persist
- Coherence rule: all writers run before any readers

Causality Issues

- Contradictory programs
- How Esterel decides whether a program is correct

What To Understand About Esterel

Compilation techniques

Automata: Fast code, Doesn’t scale

Netlists: Scales well, Slow code, Good for causality

Control-flow: Scales well, Fast code, Bad at causality