Synchronous Languages—Lecture 9

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Esterel Compilation

The 5-Minute Review Session

1. How does the constructive Boolean logic (intuitionistic logic) differ from classical Boolean logic?
2. What is the relationship between 1. logical correctness, 2. acyclicity, 3. constructiveness, 4. delay insensitivity?
3. In hw synthesis, which Esterel statements introduce registers?
4. In the context of Esterel, what is *reincarnation*? What is *schizophrenia*?
5. How is schizophrenia dealt with in classical programming languages? Which problems does schizophrenia cause in hw synthesis?

The 5-Minute Review Session

1. In the context of Esterel, what is *reincarnation*?
2. What is *schizophrenia*?
3. What is a simple solution to the schizophrenia/reincarnation problem?
4. What is the approach by Tardieu and de Simone?
5. How do these approaches compare?

Overview

Esterel Compilation
- Automata-Based Compilation
- Netlist-Based Compilation
- Control-Flow Graph-Based Compilation
- Experimental Comparison

Compiling Esterel

- Semantics of the language are formally defined and deterministic
- Compiler must ensure that generated executable behaves correctly w.r.t. the semantics
- Challenging for Esterel

The following material is adapted with kind permission from Stephen Edwards
(http://www1.cs.columbia.edu/~sedwards/)

Compilation Challenges

- Concurrency
- Interaction between exceptions and concurrency
- Preemption
- Resumption (`pause`, `await`, etc.)
- Checking causality
- Reincarnation (schizophrenia)
  - Loop restriction generally prevents any statement from executing more than once in a cycle
  - Complex interaction between concurrency, traps, and loops can make certain statements execute more than once

Automata-based Compilation

- Given Esterel program P and an input event I, the SOS inference rules introduced earlier produce an output event O and a program derivative P'
  - From P' and subsequent input event I', can produce another program derivative P'' and further output event O'
  - Can view this as sequence of **state transitions**—from state P to state P' to state P'' etc.
- Inference rules guarantee that set of states is finite (Finite State Machine, FSM)
- First compiler simulated an Esterel program in every possible state and generated code for each one

Automata-Based Compilation

Note: Strictly speaking, the state of an Esterel program—i.e., what must be remembered from one tick to the next—includes the following:

1. The set of program counter values where the program has paused between cycles
2. Presence status of signals accessed via `pre` operator
3. Values of valued signals
4. Values of variables
5. Any state kept in the host language

Only the program counters are reflected in states of FSM

Automata Example

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

≡

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

  switch (state) {
  case 0:
    A = 1;
    state = 1;
    break;

  case 1:
    if (C) {
      B = 1;
      state = 0;
    }
    break;
  }
}
```

Automata Example

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

≡

```
switch (state) {
case 0:
  A = 1;
  B = 1;
  state = 1;
  break;

case 1:
  if (C) {
    D = 1;
    if (E) B = 1;
    state = 2;
  }
  break;

case 2:
}
```

First State

- A, B, emitted, go to second state

Second state

- if C is present, emit D, check E & emit B & go on
- otherwise, stay in second state

Third state

- Terminated

Assessment of Automata Compilation

- ☺ 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 state count
  - "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 doesn't work for most programs longer than 1000 lines
- All other techniques produce—in general—slower code

Netlist-Based Compilation

Second key insight:

- Esterel programs can be translated into Boolean logic circuits

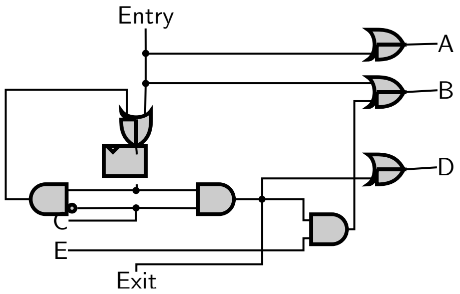
Netlist-based compiler:

- Translate each statement into a small number of logic gates
  - A straightforward, mechanical process
  - Follows circuit semantics defined earlier
- Generate code that simulates the netlist

Netlist Example

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

≡



Assessment of Netlist Compilation

- ☺ 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 ultimately irrelevant results
  - 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

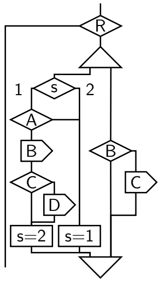
Control-Flow Graph-Based

- Third 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

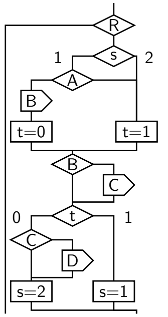
The CFG Approach

```
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
```

Esterel Source



Concurrent CFG



Sequential CFG

```
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;
      }
```

C code

Step 1: Build Concurrent CFG

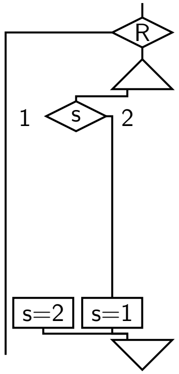
```
→every R do
   loop
     await A;
     emit B;
     present C then
       emit D end;
     pause
   end
  ||
   loop
     present B then
       emit C end;
     pause
   end
→end
```

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
```

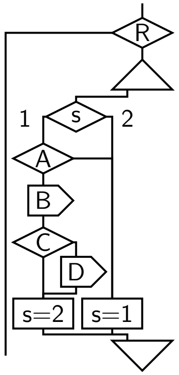
Split at Pauses

```
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
```



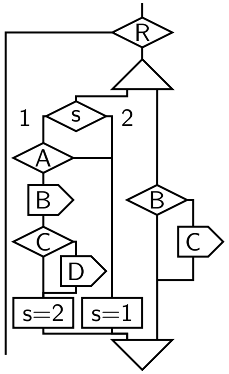
Add Code Between Pauses

```
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
```



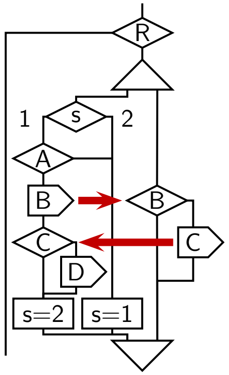
Build Right Thread

```
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
```



Step 2: Schedule

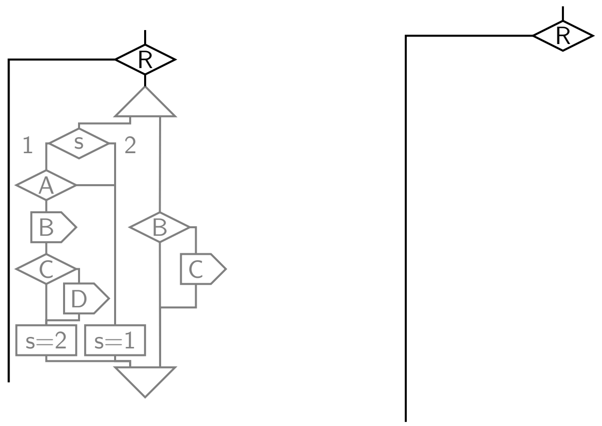
```
every R do
  loop
    await A;
    emit B;
    present C then
      emit D end;
    pause
  end
||
  loop
    present B then
      emit C end;
    pause
  end
end
```



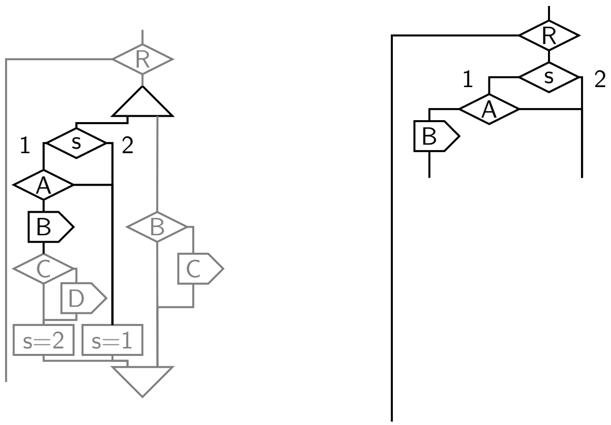
Step 3: Sequentialize

- Hardest part: Removing concurrency
- Simulate the Concurrent CFG
- Main Loop:
  - For each node in scheduled order,
  - Insert context switch if from different thread
  - Copy node & connect predecessors

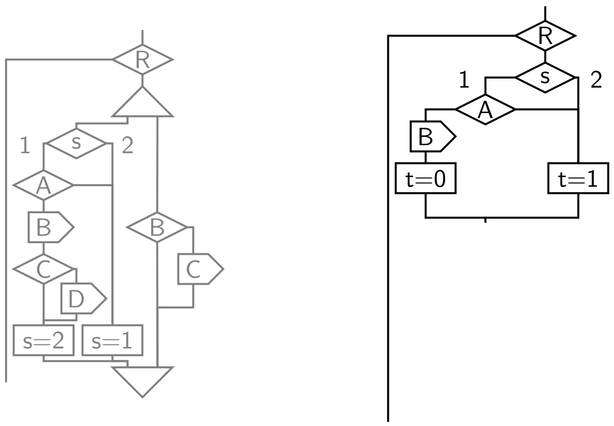
Run First Node



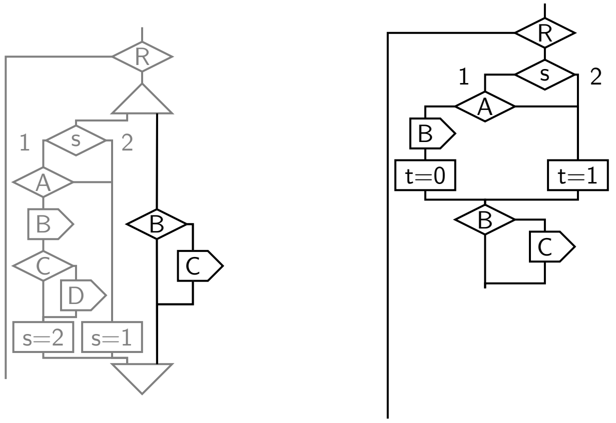
Run First Part of Left Thread



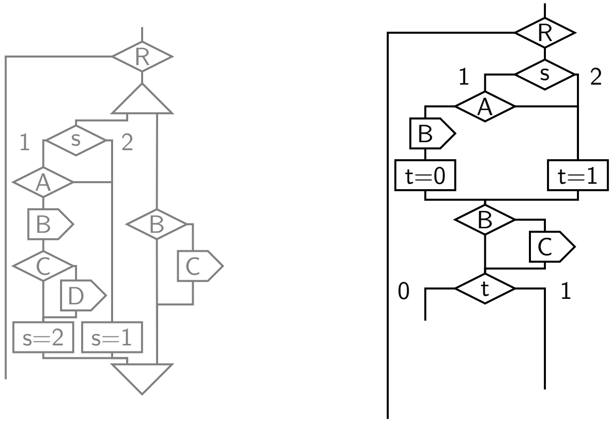
Context switch: Save State



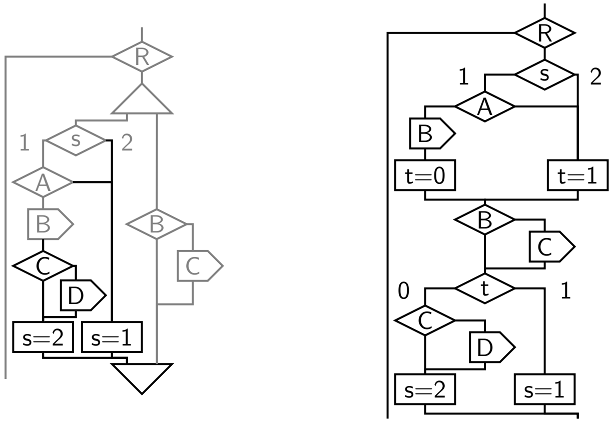
Run Right Thread



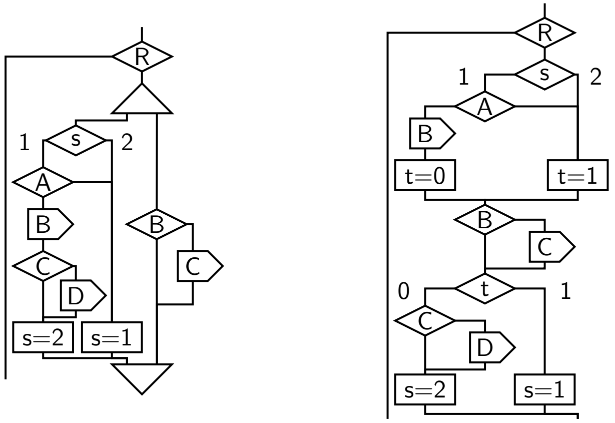
Context Switch: Restore State



Resume Left Thread



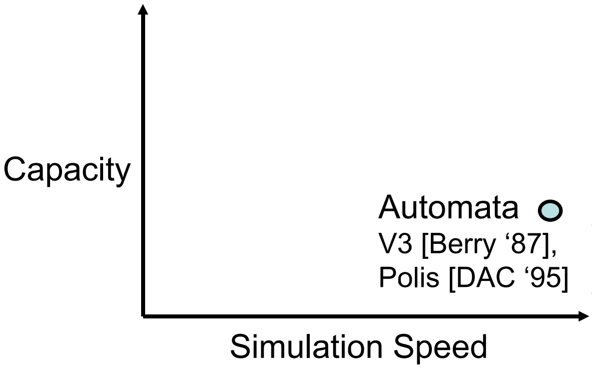
Step 3: Finished



Assessment of Control-flow Approach

- ☺ 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 that others accept
- Extension: Pre-process constructive Esterel programs with cycles into equivalent non-cyclic programs [Lukoschus/von Hanxleden 2007]
  - Extends applicability of compilation approaches such as the CFG-based approach

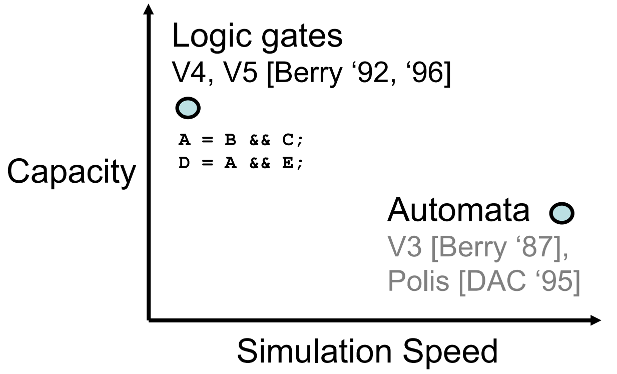
Existing Esterel Compilers



```
switch (st) {
case 0:
  st = 1;
  break;
case 1:
```

Edwards 2001

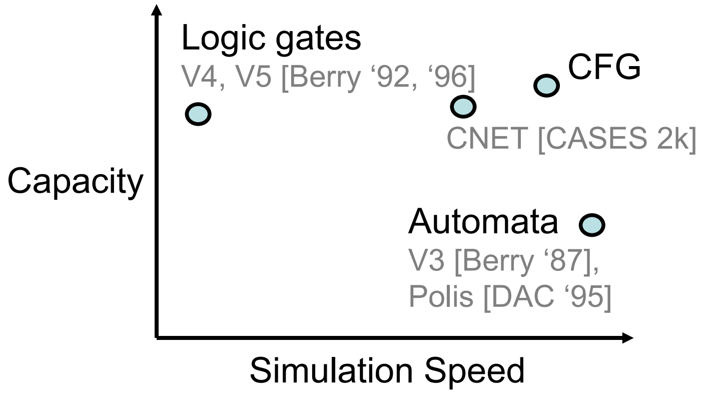
Existing Esterel Compilers



```
A = B && C;
D = A && E;
```

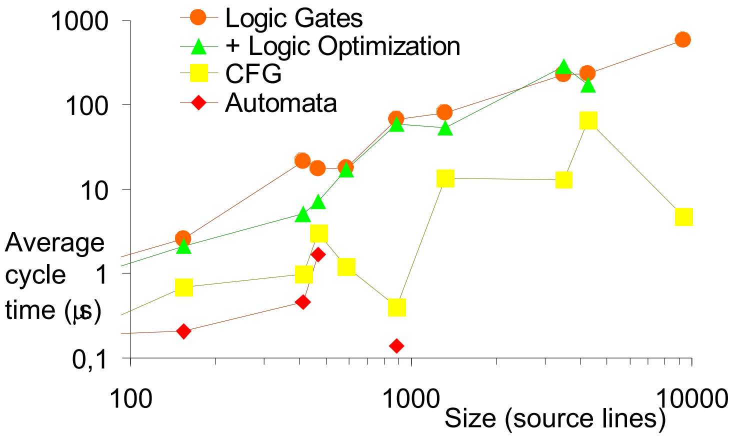
Edwards 2001

Existing Esterel Compilers



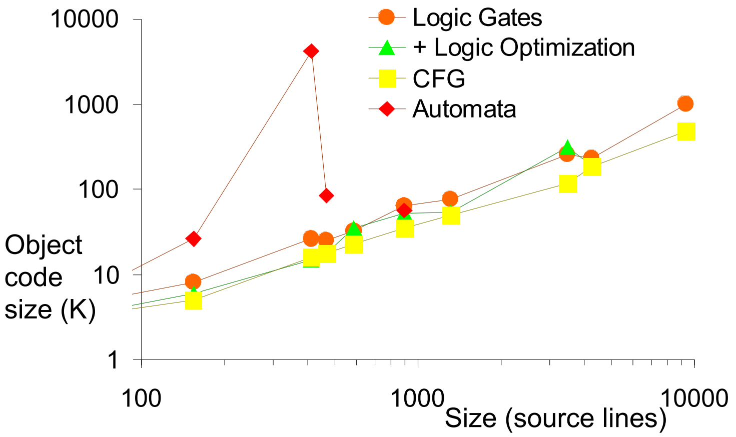
Edwards 2001

Speed of Generated Code



Edwards 2001

Size of Generated Code



Edwards 2001

Summary

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

To Go Further

- Stephen A. Edwards. Tutorial: Compiling Concurrent Languages for Sequential Processors. *ACM Transactions on Design Automation of Electronic Systems (TODAES)*, 8(2):141-187, April 2003. `http://www1.cs.columbia.edu/~sedwards/papers/edwards2003compiling.pdf`
- Stephen A. Edwards and Jia Zeng. Code Generation in the Columbia Esterel Compiler. *EURASIP Journal on Embedded Systems*, vol. 2007, Article ID 52651, 31 pages, 2007. `http://dx.doi.org/10.1155/2007/52651`
- Dumitru Potop-Butucaru, Stephen A. Edwards, and Gérard Berry. *Compiling Esterel*. Springer-Verlag, New York, 2007. ISBN 9780387706269
- Jan Lukoschus and Reinhard von Hanxleden. Removing Cycles in Esterel Programs. *EURASIP Journal on Embedded Systems, Special Issue on Synchronous Paradigms in Embedded Systems*. `http://www.hindawi.com/getarticle.aspx?doi=10.1155/2007/48979`, 2007.