Synchronous Languages—Lecture 9

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28 Nov. 2016

Last compiled: November 24, 2016, 11:48 hrs

Esterel Compilation

The 5-Minute Review Session

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5. How is schizophrenia dealt with in classical programming languages?

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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?

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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

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

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- Concurrency

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- 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.

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  - 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

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Only the program counters are reflected in states of FSM

Automata Example

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

$\equiv$

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;
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```
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

Automata Example

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emit A;
emit B;
await C;
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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

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First State

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Second state

- if C is present, emit D, check E & emit B & go on
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Third state

- Terminated

Assessment of Automata Compilation

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  - Concurrency can cause exponential state growth
  - n-state machine interacting with another n-state machine can produce n^2 states

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- ☺ **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

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Netlist-based compiler:

- Translate each statement into a small number of logic gates
  - A straightforward, mechanical process
  - Follows circuit semantics defined earlier

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;
```

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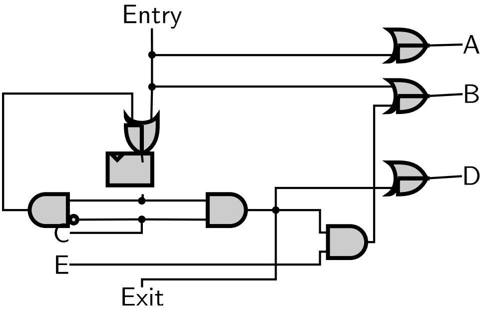

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  - Semantics of netlists straightforward
  - Constructive reasoning equivalent to three-valued simulation

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- ☺ Scales very well
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  - 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

Control-Flow Graph-Based

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

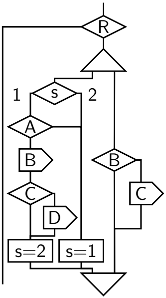
Control-Flow Graph-Based

- 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

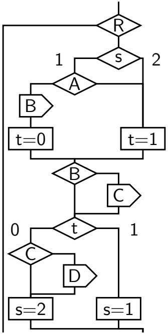
The CFG Approach

```
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



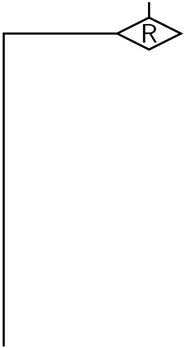
Sequential CFG

```
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
```

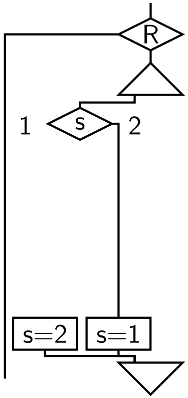


Add Threads

```
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
```

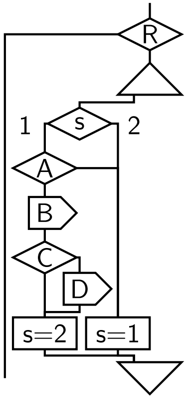
Split at Pauses

```
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
```



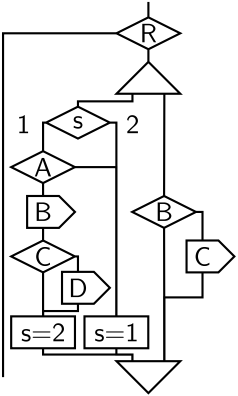
Add Code Between Pauses

```
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

```
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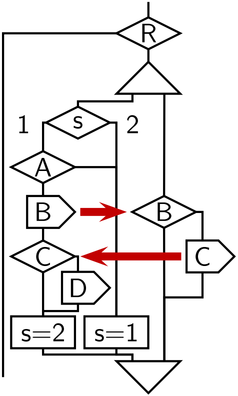
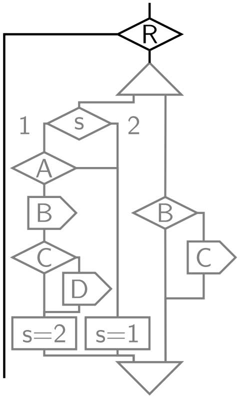


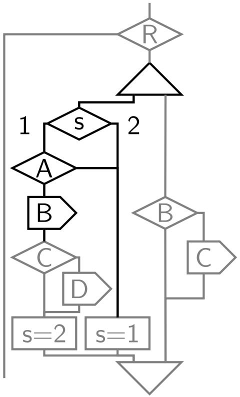
Step 3: Sequentialize

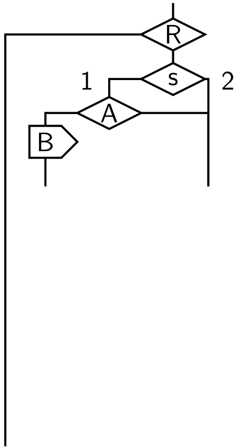
- Hardest part: Removing concurrency
- Simulate the Concurrent CFG
- Main Loop:
  - For each node in scheduled order,
  - Insert context switch if from different thread
  - Copy node & connect predecessors

Run First Node

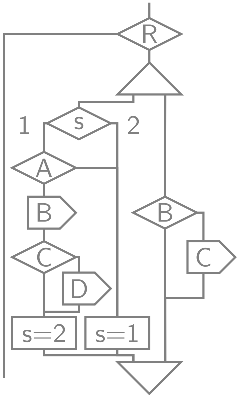


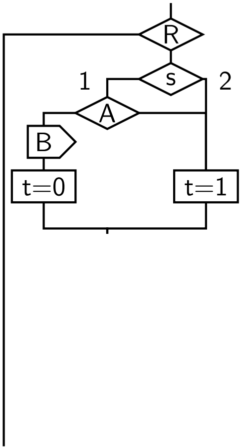
Run First Part of Left Thread



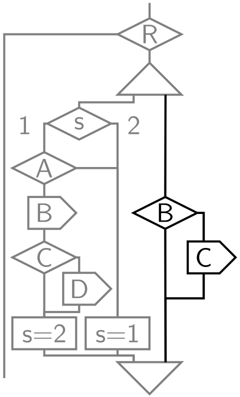


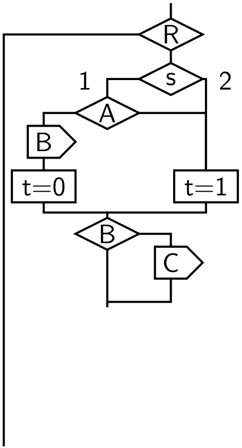
Context switch: Save State



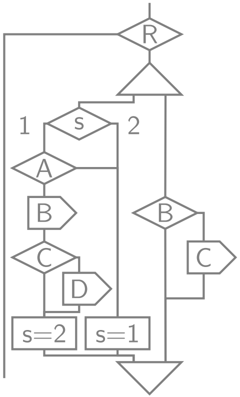


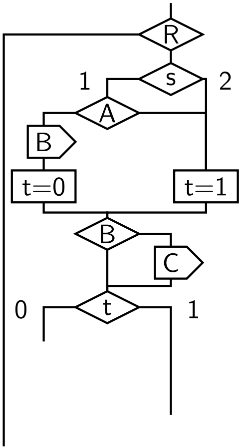
Run Right Thread



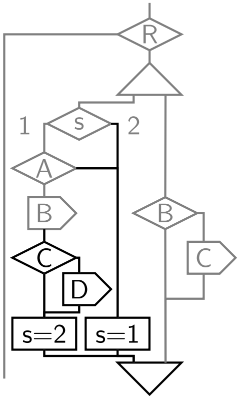


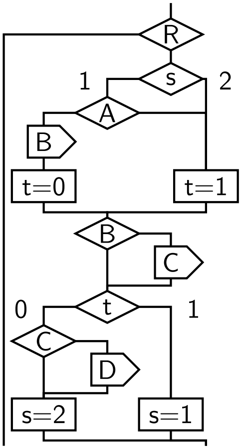
Context Switch: Restore State



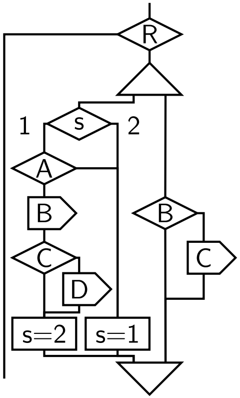


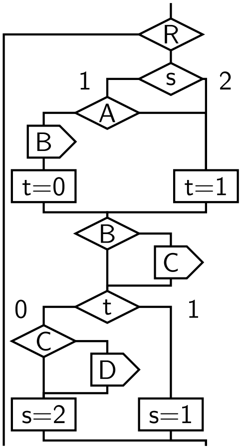
Resume Left Thread





Step 3: Finished





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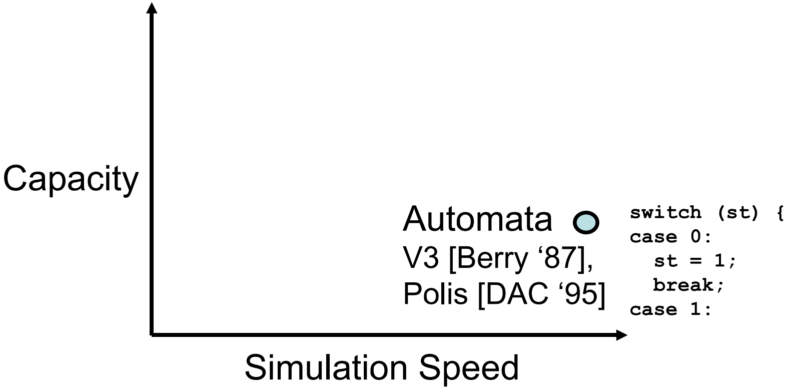
- ☹ Not an easy framework for checking causality
- ☹ Static scheduling requirement more restrictive than netlist compiler
  - This compiler rejects some programs that others accept
- Extension: Pre-process constructive Esterel programs with cycles into equivalent non-cyclic programs [Lukoschus/von Hanxleden 2007]
  - Extends applicability of compilation approaches such as the CFG-based approach

Existing Esterel Compilers



Edwards 2001

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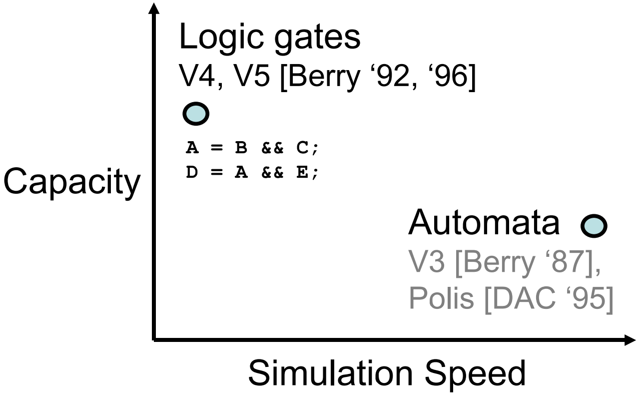

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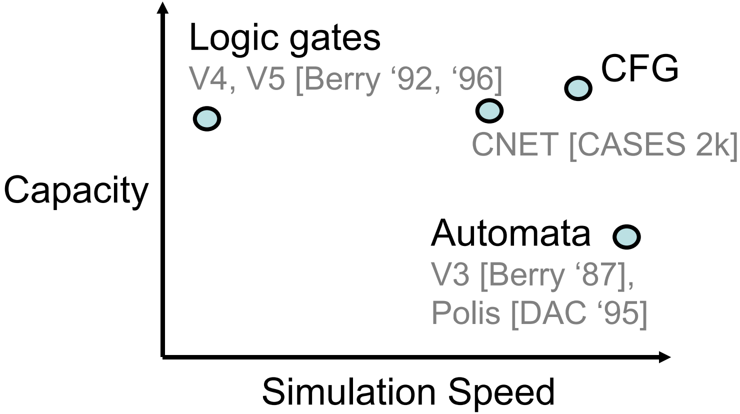

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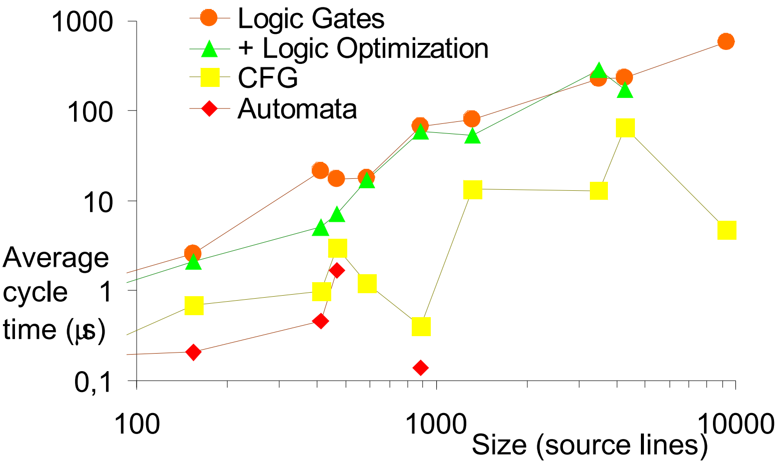
Speed of Generated Code



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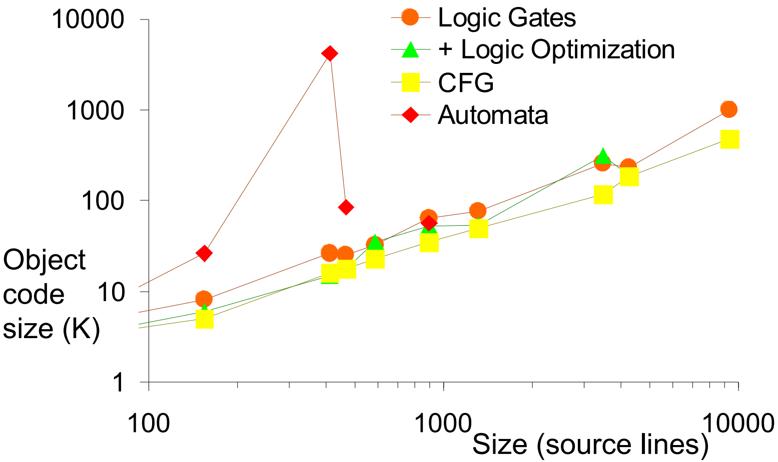
Size of Generated Code



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- 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.