Synchronous Languages—Lecture 08

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Schizophrenia Problems

The 5-Minute Review Session

1. How can we determine the *constructive behavioral semantics* of a program? (Hint: 2-step procedure)
2. When does this fail?
3. What is the difference to the *logical behavioral semantics*?
4. What is the physical explanation/equivalent for constructiveness?
5. What circuit property is equivalent to logical correctness?

Overview

Schizophrenia and Reincarnation
The Problem
Solving the Reincarnation Problem
Tardieu and de Simone (2004)

This lecture is based on material kindly provided by Klaus Schneider,
`http://rsg.informatik.uni-kl.de/people/schneider/`

Schizophrenia Problems

Recall

- Synchronous programs consist of macro steps
- Macro steps consist of micro steps
- Transition rules define micro steps

Questions:

- Can a statement be executed more than once in a macro step?
- If so, does this cause any problems?

Schizophrenic statements

- are statements that are started more than once in a macro step (eg., an emit), or left and entered in the same macrostep (eg., an abort)
- Although signal values do not change in the further starts, the repeated execution might differ!

A Related Problem with Abortion

```
loop
  abort
     emit A;
     pause;
     emit B
  when I
end loop
```

Assume the control is at the pause and `I` is present

- ⇝ `emit B` is aborted
- ⇝ `emit A` is executed

Hence, we cannot simply say that

- Weak abortion executes all actions of the macro step
- And strong abortion kills these actions

Instead, it depends on whether the actions belong to the surface of the abort statement or to its depth

- Surface of a statement: parts that are reachable in one macrostep.
- Depth of a statement: all parts reachable in later macrosteps.

Example for Schizophrenic Emission

```
loop
  present I then
    pause
  end present;
  emit A;
||
  pause
end loop
```

- The previous example was not yet schizophrenic
- However, consider `Schizo1` on the left
- Assume `I` was present in the first instance and is absent in the second
  - ⇝ `emit A` is executed
  - ⇝ `loop` restarts its body
  - ⇝ `present I` ... is skipped
  - ⇝ `emit A` is executed twice
- Hence, schizophrenic statements exist

Schizophrenic Actions

- Is it a problem that statements may be executed more than once in a macro step?
- Since the value of a valued signal is always computed for a whole macrostep, it appears (at a first glance) not to be a problem
  - Executing `emit S` more than once makes `S` present
  - Executing `emit(S(i))` more than once has the same effect as the execution of multiple `emit(S(i))`
- So, the synchrony of the valued signal updates and the causal ordering of variable updates seems to make everything consistent
- However, scopes of local variables may be re-entered
- This can change the environment in micro steps

⇝ *Reincarnation problem*

The Reincarnation Problem

- The reincarnation problem is related to schizophrenia
- Reincarnation takes place, iff a local declaration is left and re-entered within the same macro step
- This is not necessarily a problem
- However, it may lead to unexpected behaviours
- In particular, in combination with schizophrenic statements, since **these may behave different in the second execution**

The Simplest Example for Reincarnation

```
loop
  signal S in
    present S then
      emit S_on
    else
      emit S_off
    end;
    pause
    emit S;
    present S then
      emit S_on
    else
      emit S_off
    end;
  end signal
end loop
```

- If control starts at the pause, then `S` is emitted
- Second conditional emits `S_on`
- Scope of local signal is left
- Loop restarts its body
- Scope of local signal is entered
- First conditional emits `S_off`
- Control stops at `pause`

⇝ *Both S_on and S_off are present for $t > 0$*

Compilation to Software

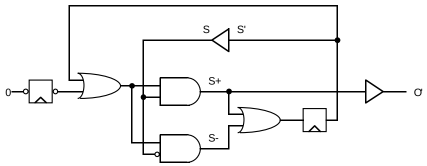
- Reincarnating local declarations is well-known from sequential imperative languages
- It is handled by maintaining a stack that holds the current visible variables together with their values
- If a local declaration is entered, an entry for the variable is put on the stack
- During execution, the values of the variables on the stack may be changed; to this end, the stack is searched from top to bottom to find a variable
- If a local declaration is left, the entry is deleted from the stack

⇝ No problem in software

Schizophrenia

```
module P17:
output O;
loop
  signal S in
    present S
      then emit O
    end present;
    pause;
    emit S;
  end signal
end loop
end module
```

≡



- The circuit resulting from the translation rules (as given so far) does not behave as P17!
- The Problem: The circuit translation rules do not consider signal scoping rules
- Different signal incarnations are treated as identical

Compilation Problem

The proposed hardware synthesis can still be used with the following adaptions:

- generate copies of locally declared signals (one for the surface and one for the depth)
- decide for every occurrence of these signals which copy is meant

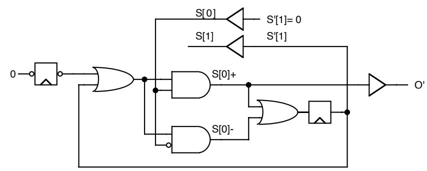
Note: more than one copy may be required this way
⇝ multiple reincarnation

- The circuit behaves as if there were just one instance of S
- Hence, O is emitted from the second instance on
- The equivalent Esterel program would be as P17, but with the signal declaration interchanged with the loop

Schizophrenia

```
module P17:
output O;
loop
  signal S in
    present S
      then emit O
    end present;
    pause;
    emit S;
  end signal
end loop
end module
```

≡



- In this circuit, signal is handled correctly by separating surface and depth

Multiple Reincarnation

```
loop                 (a)
  trap T1 in
    pause;           (1)
    exit T1
  ||
    loop             (b)
      trap T2 in
        pause;       (2)
        exit T2
      ||
        loop         (c)
          emit O(1);
          pause      (3)
        end loop
      end trap
    end loop
  end trap
end loop
```

- `O` is an integer signal, combined by +
- After first macrostep, control rests on all three pause statements in parallel
- In the second macrostep:
  - pause (3) is left → restart loop (*c*) → `O(1)` emitted
  - pause (2) is left → execute `exit T2` → restart loop (*b*) → emit `O(1)`
  - pause (1) is left → execute `exit T1` → restart loop (*a*) → emit `O(1)`

⇝ `O(1)` is emitted three times

This example can easily be extended to even more reincarnations. Hence a statement can be restarted arbitrarily often in one macrostep.

Multiple Reincarnation

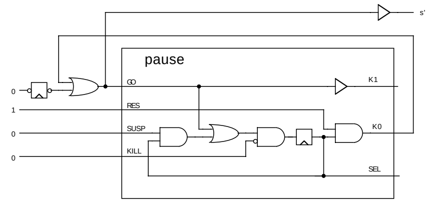
- Nested loops may even lead to multiple reincarnations
- Note: leaving and restarting a local declaration can only be done by a surrounding loop
- Number of nested loops around the local declaration corresponds with the number of possible reincarnations
- Remark: generated copies can, in principle, be substituted, however, the compilation is then even more complicated

Schizophrenia

- Schizophrenia can be a problem even without local signal reincarnations
- To illustrate, first consider the following circuit translation (which is equivalent to `sustain S`):

```
module SUSTAIN:
output S;
loop
  emit S;
  pause
end loop;
end module
```

≡



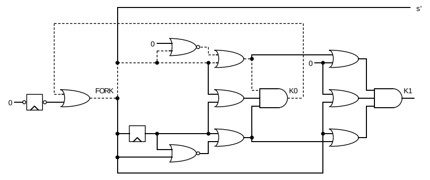
- `K0` output of pause subcircuit feeds back to the `GO` input
- However, signal levels are always fully determined

Schizophrenia

- Now consider the circuit translation for P16, which should be equivalent to SUSTAIN:

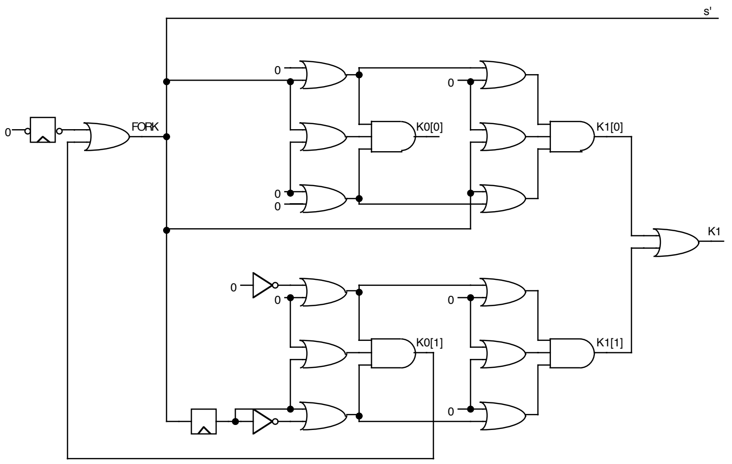
```
module P16:
output S;
loop
  emit S;
  [nothing || pause]
end loop;
end module
```

≡



- This circuit contains an unstable combinational loop (see dotted lines)
- Hence, the circuit is not constructive!
- The problem: reincarnation of parallel

Schizophrenic Synchronizer



Correct circuit of (!s; (0 | 1))*

Solutions to the Reincarnation Problem

Problematic for hardware circuit synthesis

- Variables are translated to wires and registers
- Wires must have unique values for every cycle!

Questions

- Do schizophrenic local declarations require more than one wire?
- How to separate the scopes in the circuit?

Solutions:

- Simple loop duplication
- Poigné and Holenderski (1995) $\rightsquigarrow$ circuit level
- Berry (1996/1999) $\rightsquigarrow$ circuit level
- Schneider and Wenz (2001) $\rightsquigarrow$ program level
- Tardieu and de Simone (2004) $\rightsquigarrow$ program level

Reincarnation: Simple Solution

- A simple approach to eliminate schizophrenia (and hence reincarnation), is to duplicate loop bodies:

`loop p end` $\Rightarrow$ `loop p;p end`

- Since *p* is not instantaneous, no part of *p* can be restarted immediately
- We have to do this recursively

$\rightsquigarrow$ Worst-case increase of program size: Exponential

Tardieu and de Simone (2004)

- Add unique labels to each pause statement
- New Esterel statement `gotopause` jumps to a labeled `pause`
- Define function *surf*(p) to compute surface of p as:
  - *surf*(`loop` p `end`) = *surf*(p)
  - *surf*(p;q) = *surf*(p); *surf*(q) if p can be instantaneous
  - *surf*(p;q) = *surf*(p) otherwise
  - *surf*(ℓ : `pause`) = `gotopause` ℓ
- Define function *dup*(p) that expands `loop` bodies:
  - *dup*(`loop` p `end`) = `loop` *surf*(p);*dup*(p) `end`
- Omitted rules correspond to simple recursive calls

Example with gotopause

Expand loop body by applying dup():

```
loop
  signal S in
    present S then emit O end;
    pause;
    emit S;
  end;
  present I then emit O end;
end loop
```

```
loop
  signal S in
    present S then emit O end;
    gotopause 1;
  end;
  signal S in
    present S then emit O end;
    1: pause;
    emit S
  end;
  present I then emit O end;
end loop
```

- Optimization: remove dead code

Tardieu and de Simone (2004)

- Program size grows quadratic in worst case, but linear in practice
- As by Schneider and Wenz, no new registers are introduced
- But there is still room for improvement ...
- Observation 1: Whether a program p is instantly re-started depends on both p and the context of p

```
trap T in
  loop
    p1
  end loop
end trap
```

```
loop
  trap T in
    p2;
    pause
  end trap
end loop
```

- p_1 is instantly restarted when it returns completion code 0
- p_2 is instantly restarted when it returns completion code 2

Note: We are not just considering completion codes at the instant when the p_i are started, but all completion codes that the p_i may return at any point during their execution

Tardieu and de Simone (2004)

Based on Observation 1, the program transformation can be enhanced with static program analysis

- Compute potential completion codes for each program fragment *p*
- Compute unsafe completion codes for the context of *p*
- If intersection is not empty, then *p* is potentially schizophrenic

Observation 2: Only signal declarations and parallel statements can lead to schizophrenic behavior

- The improved transformation does not blindly duplicate whole loop bodies, but instead duplicates only potentially schizophrenic signal declarations and parallel statements

To Go Further

- Gérard Berry, The Constructive Semantics of Pure Esterel, Draft book, current version 3.0, Dec. 2002, Chapter 12, `http://www-sop.inria.fr/members/Gerard.Berry/Papers/EsterelConstructiveBook.zip`
- Klaus Schneider and M. Wenz, A New Method for Compiling Schizophrenic Synchronous Programs, CASES 2001, `http://es.cs.uni-kl.de/publications/datarsg/ScWe01.pdf`
- Oliver Tardieu and Robert de Simone, Curing Schizophrenia by Program Rewriting in Esterel, MEMOCODE 2004 `http://www1.cs.columbia.edu/~tardieu/papers/memocode04.pdf`