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)

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

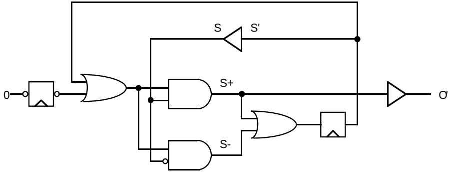
- Reincarnating local declarations is well-known from sequential imperative languages
- It is handled by maintaining a stack that holds the current visible variables together with their values
- If a local declaration is entered, an entry for the variable is put on the stack
- During execution, the values 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

$\rightsquigarrow$ 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:

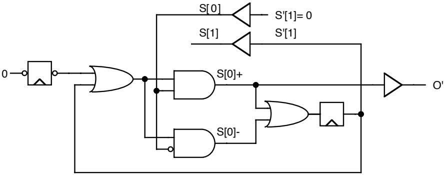
- generate copies of locally declared signals (one for the surface and one for the depth)
- decide for every occurrence of these signals which copy is meant

Note: more than one copy may be required this way
$\rightsquigarrow$ multiple reincarnation

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 $\rightarrow$ restart loop (c) $\rightarrow$ O(1) emitted
  - pause (2) is left $\rightarrow$ execute exit T2 $\rightarrow$ restart loop (b) $\rightarrow$ emit O(1)
  - pause (1) is left $\rightarrow$ execute exit T1 $\rightarrow$ restart loop (a) $\rightarrow$ emit O(1)

$\leadsto$ O(1) is emitted three times

Multiple Reincarnation

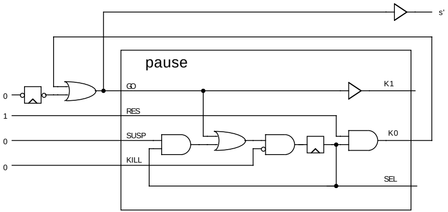
- Nested loops may even lead to multiple reincarnations
- Note: leaving and restarting a local declaration can only be done by a surrounding loop
- Number of nested loops around the local declaration corresponds with the number of possible reincarnations
- Remark: generated copies can, in principle,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

≡



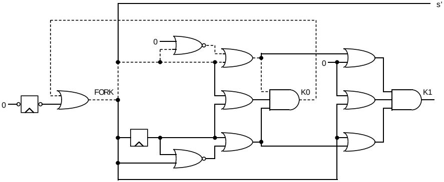
- `K0` output of pause subcircuit feeds back to the `GO` input
- However, signal levels are always fully determined

Schizophrenia

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

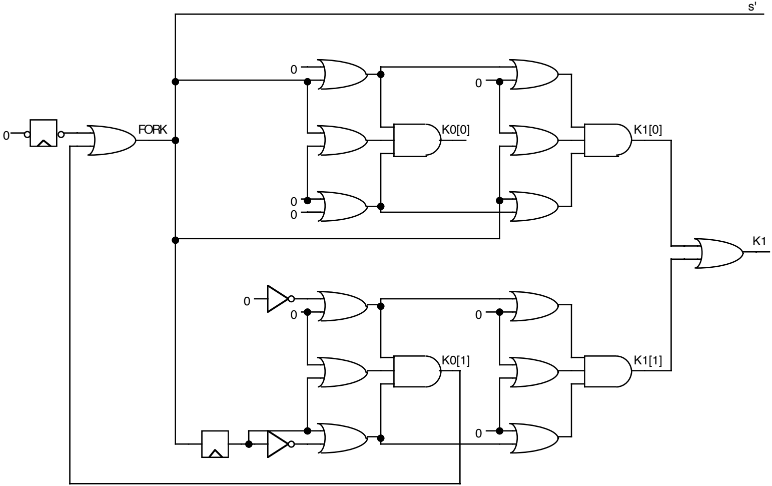
```
module P16:
output S;
loop
  emit S;
  [nothing || pause]
end loop;
end module
```

≡



- 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

$\leadsto$ 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 $\mathit{surf}(p)$ to compute surface of p as:
  - $\mathit{surf}(\texttt{loop}\ p\ \texttt{end}) = \mathit{surf}(p)$
  - $\mathit{surf}(p\,\texttt{;}\,q) = \mathit{surf}(p)\texttt{;}\ \mathit{surf}(q)$ if p can be instantaneous
  - $\mathit{surf}(p\,\texttt{;}\,q) = \mathit{surf}(p)$ otherwise
  - $\mathit{surf}(\ell : \texttt{pause}) = \texttt{gotopause}\ \ell$
- Define function $\mathit{dup}(p)$ that expands `loop` bodies:
  - $\mathit{dup}(\texttt{loop}\ p\ \texttt{end}) = \texttt{loop}\ \mathit{surf}(p)\texttt{;}\mathit{dup}(p)\ \texttt{end}$
- 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 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

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`