The Linear Time – Branching Time Spectrum after 20 years

or

Full abstraction for safety and liveness properties

Rob van Glabbeek

NICTA, Sydney, Australia

University of New South Wales, Sydney, Australia

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Time permitting, at the end of my talk I will make some comments on the rest of the semantic lattice, and my current view on the linear time branching time spectrum.
Labelled Transition Systems

I focus on processes modelled as states in an LTS \( (P, \rightarrow) \), where \( P \) is a set of states (or \textit{processes}) and \( \rightarrow \subseteq P \times \text{Act}_\tau \times P \) the \textit{transition relation} for some set of \textit{visible actions} \( \text{Act} \) augmented with the \textit{invisible action} \( \tau \notin \text{Act} \).

Thus, I abstract from probabilistic choice, real-time, etc.

Let \( a, b, c, \ldots \) range over \( \text{Act} \) and \( \alpha, \beta, \ldots \) over \( \text{Act}_\tau \).

An \( \alpha \)-labelled transition from process (state) \( p \) to \( q \) is denoted \( p \xrightarrow{\alpha} q \).

However, when explaining the difference between parallel composition and interleaving operators, I implicitly use Petri Nets or an enriched form of LTS as my system model.
Partially synchronous parallel composition

\[ a \parallel b \parallel \{b\} \]

as in CSP.
Hiding operators

Abstraction from the action $b$:

rename $b$ into the hidden action $\tau$. 
Semantic equivalences

A useful semantic equivalence \( \sim \) between processes (e.g. states in an LTS) has to satisfy two crucial requirements:

(1) Let \( \Phi \) be the set of properties of processes that are important in applications.
If \( p \sim q \) and \( p \) satisfies some property from \( \Phi \), then so does \( q \).
In order words, equivalent processes should have the same important properties.
Or, if \( p \) has an important property that \( q \) does not have, they better be distinguished by \( \sim \).

(2) If applications can be build by putting a process \( p \) in a context \( C[p] \) (such as a parallel composition \( p \parallel r \)), then

\[
p \sim q \implies C[p] \sim C[q].
\]
Two crucial requirements of useful $\sim$:

1. respect important properties $\varphi \in \Phi$:
   $p \sim q \Rightarrow p \models \varphi \iff q \models \varphi$

2. compositionality (or congruence):
   $p \sim q \Rightarrow C[p] \sim C[q]$.
Preorders

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1. $\sqsubseteq$ respects good properties $\varphi \in \Phi$:
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(Note: if $\varphi$ is a good property, then $\neg \varphi$ is a bad property.)
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- The second property becomes monotonicity:
  \[ p \sqsubseteq q \Rightarrow C[p] \sqsubseteq C[q]. \]
The semantic lattice

We can order semantic equivalences by *distinguishing power*, drawing the “strongest”, “most discriminating”, or “finest” above.

They form a complete lattice: any collection of equivalences has a least upperbound and a greatest lowerbound.
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Full abstraction

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- $\bullet$: coarsest preorder satisfying (1) and (2).
  Given by $p \sqsubseteq q \Leftrightarrow \forall C[]. \forall \varphi. C[p] \models \varphi \Rightarrow C[q] \models \varphi.$
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above the red line:
all satisfying (1) and (2).
The good properties to consider are

- **Safety properties:**
  
  *Something bad will never happen*

- **Liveness properties:**
  
  *Something good will happen eventually*

- **Conditional liveness properties (to be explained).**
Safety properties

Let $b$ be a special action, saying that something \textbf{bad} happens. A \textit{trace} of a process $p$ is the sequence of visible actions resulting from an execution starting in state $p$. Now my specific safety property says that a process has no trace in which the action $b$ occurs. $b$ will never happen
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A general safety property is a set $B$ of sequences of actions, thought of as all those traces that are bad for us, or make us unhappy for whatever reason. A process satisfies this general safety property iff it allows no traces in $B$.
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- Theorem: A congruence for hiding and parallel composition respects every general safety property iff it respects the specific safety property above.

- The preorder which is fully abstract w.r.t. safety properties and parallel composition and hiding is reverse trace inclusion:

$$p \sqsubseteq_{\text{safety}} q \iff \text{traces}(p) \supseteq \text{traces}(q)$$
Liveness properties

Let $g$ be a special action, saying that something good happens. A trace is completed if it is the visible context of a maximal execution, that is either infinite, or ends in a deadlock state, from which no further transitions are possible.

Now my specific liveness property says that in every completed trace of $p$ the action $g$ occurs. $g$ will eventually happen.
Liveness properties

- Let $g$ be a special action, saying that something **good** happens. A trace is *completed* if it is the visible context of a *maximal* execution, that is either infinite, or ends in a *deadlock state*, from which no further transitions are possible. Now my specific liveness property says that in every completed trace of $p$ the action $g$ occurs. **$g$ will eventually happen**

- A **general liveness property** is a set $G$ of sequences of actions, thought of as all those traces that are good for us, or make us happy for whatever reason. A process satisfies this general liveness property iff it allows only completed traces in $G$. 
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- The preorder which is fully abstract w.r.t. liveness properties and a form of parallel composition and hiding has been characterised by De Nicola & Hennessy as the **must-testing preorder**; it the CSP **failures and divergences preorder**.
May-testing versus safety preorder

- [DH84] defines the *may-testing* preorder $\sqsubseteq_{\text{may}}$, which amounts to trace inclusion, and the *must-testing* preorder $\sqsubseteq_{\text{must}}$. Then the combined testing preorder is given by

\[ p \sqsubseteq_{\text{testing}} q \text{ iff } p \sqsubseteq_{\text{may}} q \text{ and } p \sqsubseteq_{\text{must}} q. \]
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- First of all, the safety preorder is the **reverse** of the may-testing preorder. The process $ab + ac$ may do the action $b$. In may-testing semantics $ab + ac$ is a good implementation of $ab$, because everything that $ab + ac$ may do, also $ab$ may do. In the safety preorder, the ability to do $b$ is a bad thing, which reverses the preorder.
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- Therefore, my first modification of the testing preorder is that I take $\sqsubseteq_{\text{may}} \cap \sqsubseteq_{\text{must}}$ rather than $\sqsubseteq_{\text{may}} \cap \sqsubseteq_{\text{must}}$. 
The limits of must-testing

In must-testing semantics these two processes are identified:

1. \( \tau \)
2. \( i \rightarrow g \rightarrow \tau \)
3. \( i \rightarrow \tau \)

\[ \equiv_{\text{must}} \]

In neither case can we be sure that the good action \( g \) will eventually happen. These two processes satisfy the same liveness properties.
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$$
\tau \xrightarrow{i} g \equiv_{\text{must}} \tau \xrightarrow{i}
$$

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- Now think of the action $i$ as an investment, that costs us $10,000, and of $g$ as the investment paying off...
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\[ i \quad \begin{array}{c} \longrightarrow \\ \longrightarrow \end{array} \quad \begin{array}{c} g \quad \begin{array}{c} \longrightarrow \\ \longrightarrow \end{array} \quad \begin{array}{c} \equiv \text{must} \end{array} \quad i \end{array} \]

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- The must-testing preorder does not respect conditional liveness properties.
Conditional liveness properties

Let $i$ be an action that indicates a cost or investment, and $g$ be the signal that this investment pays off. Now my specific liveness property says that in every completed trace of in which the action $i$ occurs, $g$ occurs as well. provided $i$ occurs, $g$ will eventually happen.
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- A general conditional liveness property is a pair \((\sigma, G)\) of a sequence of actions \(\sigma\) and a set of sequences of actions \(G\). A process satisfies this general liveness property iff it allows only completed traces with the property that each completed trace with prefix \(\sigma\) occurs in \(G\).
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- Theorem: A congruence for hiding and parallel composition respects every general conditional liveness property iff it respects the specific conditional liveness property above.
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- A \textit{general conditional liveness property} is a function from the set of finite sequences of actions to the real numbers. This function indicates for each occurrence of an action in a complete trace how much profit or loss ones makes by executing this action, namely the value associated to the sequence of visible actions seen so far. A process satisfies this general liveness property iff each of its completed traces sums to a positive value.
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- The preorder which is fully abstract w.r.t. these conditional liveness properties is also a congruence for normal liveness properties as well as safety properties.
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- It coincides with the coarsest congruence respecting combined deadlock and divergence traces.
- The latter has been characterised by Antti Puhakka: a process is determined by its:
  - divergence traces
  - eventually nondivergent infinite traces
  - and nondivergent failure pairs.
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\[
p \sqsubseteq_{\text{cond. liveness}} q \iff \begin{align*}
\text{div.traces}(p) & \supseteq \text{divtraces}(q) \\
\text{e.nd.inf.tr}(p) & \supseteq \text{e.nd.inf.tr}(q) \\
\text{nd.fail}(p) & \supseteq \text{nd.fail}(q)
\end{align*}
\]
Parallel composition versus interleaving

- In [DH84] must-testing semantics, or in [BHR84] failures semantics, **livelock** and **deadlock** are distinguished:
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  ![Diagram](image)

  \[ \tau \not\equiv \text{must} \]

- The reason: when interleaving both process with the process \( a \) we get:

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- It is not possibly to distinguish the original two processes when using parallel composition instead of interleaving!
Must-testing without interleaving
To define testing semantics with parallel composition instead of interleaving, we take any model of concurrency that administers which transitions originates from the same component in a parallel composition. A trace now counts as completed only if it is completed in each parallel component.

This parallel composition does not have a completed trace without the $a$ action.
Must-testing with parallel comp. implies cond. liveness

- These two processes were identified in must-testing semantics, although they are distinguished by a cond. liveness property:

\[
\begin{align*}
\tau & \quad \quad i \quad \quad g \\
\tau & \quad \quad i
\end{align*}
\]

\[
\equiv_{\text{must}}
\]

\[
\begin{align*}
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\[
\neq
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\[ \tau \quad i \quad g \quad \equiv_{\text{must}} \quad \tau \quad i \]

\[ \tau \quad i \quad g \quad \parallel \{i,g\} \quad \omega \quad \omega \quad = \quad \tau \quad i \quad g \quad \omega \quad \omega \]

\[ \tau \quad i \quad g \quad \omega \quad \omega \quad \neq \quad \tau \quad i \quad \omega \quad \omega \]

- On sequential processes resulting preorder exactly as before, but with extra identification of deadlock and livelock.
Conclusions / Position statement

- A useful semantic equivalence
  - respects important properties of processes
  - is compositional w.r.t important composition operators
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- Given agreement on these properties and operators, the above two requirements determine a unique best semantics
  This semantics is fully abstract w.r.t. the given collection of properties and operators.
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  - complexity of decision procedures
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    - guarded fixed point equations have unique solutions

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  This semantics is *fully abstract* w.r.t. the given collection of properties and operators.

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- Different applications require different *properties* and *operators*; there is no canonical choice.

- In the absence of agreement on which properties and operators to use, the finest (branching time) semantics are best.
Conclusions / Position statement

- A good semantics should respect the following properties
  - Safety properties
  - Liveness properties (possibly assuming fairness)
  - Conditional liveness properties (possibly assuming fairness)
  - (perhaps) AGEF properties

Many other properties, such as preservation of deadlock behaviour, are not really important.
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- abstraction from internal activity
- (partially synchronous) interleaving operator

I believe it makes sense to use a (partially synchronous) parallel composition instead (while employing interleaving semantics by abstracting from causality etc).
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- Other operators may be needed depending on the application. A good example are priority operators.
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- Must testing is fully abstract for liveness properties (w.r.t. abstraction and interleaving) De Nicola & Hennessy 1984
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- The must-testing preorder is not strong enough. It is fully abstract for liveness properties but misses out on conditional liveness properties, which are just as important.
- I presented a finer semantics that is fully abstract for safety and conditional liveness properties w.r.t. abstraction and interleaving.
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Conclusions / Position statement

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I propose a new semantics that is fully abstract for safety and (conditional) liveness properties w.r.t. hiding and parallel composition.