Linear Temporal Logic, Critical Sections and Promela Modelling

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Where are we?

**Last Lecture**

We saw how to treat the semantics of concurrent programs and the properties they should satisfy.

**This Lecture**

We will give a syntactic way to specify properties (Temporal Logic) and introduce one of two methods we will cover to show properties hold (Model Checking) using the famous Critical Section problem.
We typically state our requirements with a logic.
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Definition
A logic is a formal language designed to express logical reasoning. Like any formal language, logics have a syntax and semantics.
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**Example (Propositional Logic Syntax)**

- A set of atomic propositions \( \mathcal{P} = \{a, b, c, \ldots \} \)
- An inductively defined set of formulae:
  - Each \( p \in \mathcal{P} \) is a formula.
  - If \( P \) and \( Q \) are formulae, then \( P \land Q \) is a formula.
  - If \( P \) is a formula, then \( \neg P \) is a formula.

(Other connectives are just sugar for these, so we omit them)
Semantics

Semantics are a mathematical representation of the meaning of a piece of syntax. We will use models to give semantics to logic.

Example (Propositional Logic Semantics)

A model for propositional logic is a valuation \( V \subseteq P \), a set of "true" atomic propositions. We can extend a valuation over an entire formula, giving us a satisfaction relation:

- \( V \models p \iff p \in V \)
- \( V \models \phi \land \psi \iff V \models \phi \) and \( V \models \psi \)
- \( V \models \neg \phi \iff V \not\models \phi \)

We read \( V \models \phi \) as \( V \) "satisfies" \( \phi \).
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Example (Propositional Logic Semantics)

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\[
\begin{align*}
\mathcal{V} \models p & \iff p \in \mathcal{V} \\
\mathcal{V} \models \varphi \land \psi & \iff \mathcal{V} \models \varphi \text{ and } \mathcal{V} \models \psi \\
\mathcal{V} \models \neg \varphi & \iff \mathcal{V} \not\models \varphi
\end{align*}
\]

We read \( \mathcal{V} \models \varphi \) as \( \mathcal{V} \) “satisfies” \( \varphi \).
Linear temporal logic (LTL) is a logic designed to describe linear time properties.

Linear temporal logic syntax

We have normal propositional operators:

- $p \in P$ is an LTL formula.
- If $\varphi, \psi$ are LTL formulae, then $\varphi \land \psi$ is an LTL formula.
- If $\varphi$ is an LTL formula, $\neg \varphi$ is an LTL formula.
**Linear Temporal Logic**

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We also have modal or temporal operators:

- If $\varphi$ is an LTL formula, then $\Diamond \varphi$ is an LTL formula.
- If $\varphi, \psi$ are LTL formulae, then $\varphi \mathcal{U} \psi$ is an LTL formula.
LTL Semantics in Pictures

\[ \sigma \]

1. \( \emptyset \)
2. \( \{ \spadesuit \} \)
3. \( \{ \heartsuit \} \)
4. \( \{ \heartsuit \} \)
5. \( \{ \spadesuit \} \)
LTL Semantics in Pictures
LTL Semantics in Pictures
LTL Semantics in Pictures

\[ \sigma \]

\[ \emptyset \rightarrow \{ \heartsuit \} \rightarrow \{ \heartsuit \} \rightarrow \{ \heartsuit \} \rightarrow \{ \spadesuit \} \rightarrow \{ \spadesuit \} \]

\[ \neg \heartsuit, \neg \spadesuit \]

\[ \neg (\heartsuit U \spadesuit) \]

\[ \heartsuit U \]

\[ \heartsuit U \]

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LTL Semantics in Pictures

$$\sigma \xrightarrow{\emptyset} \{\heartsuit\} \xrightarrow{\{\spadesuit\}} \{\heartsuit\} \xrightarrow{\{\heartsuit\}} \{\heartsuit\} \xrightarrow{\{\spadesuit\}} \{\spadesuit\}$$

$$\neg \heartsuit, \neg \spadesuit, \neg (\heartsuit U \spadesuit) \quad \neg \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit$$
LTL Semantics in Pictures

σ

∅ → {♠} → {♥} → {♥} → {♥} → {♠}

¬♥, ¬♠, ¬♥, ♥, ¬♠, ¬♠, ¬♠, ¬♠, ¬♥, ¬♠, ¬♥, ♥

¬(♥ U ♠)
LTL Semantics in Pictures

\[ \sigma \]

\[ \emptyset \rightarrow \{ \spadesuit \} \rightarrow \{ \heartsuit \} \rightarrow \{ \heartsuit \} \rightarrow \{ \heartsuit \} \rightarrow \{ \spadesuit \} \]

\[ \neg \heartsuit, \neg \spadesuit \quad \neg \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \quad \heartsuit, \neg \spadesuit \]
LTL Semantics in Pictures

\[
\sigma \quad \emptyset \quad \{\heartsuit\} \quad \{\diamondsuit\} \quad \{\heartsuit\} \quad \{\heartsuit\} \quad \{\diamondsuit\}
\]

\[\neg \heartsuit, \neg \diamondsuit \quad \neg \heartsuit, \heartsuit \quad \heartsuit, \neg \diamondsuit \quad \heartsuit, \heartsuit \quad \heartsuit, \neg \diamondsuit \quad \neg \heartsuit, \heartsuit \]

\[\neg (\heartsuit U \diamondsuit) \quad \heartsuit U \diamondsuit \quad \heartsuit U \diamondsuit \quad \heartsuit U \diamondsuit \quad \heartsuit U \diamondsuit \quad \heartsuit U \diamondsuit \]
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LTL Semantics in Pictures

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\[ \neg(\heartsuit \cup \spadesuit) \quad \heartsuit \cup \spadesuit \quad \heartsuit \cup \spadesuit \quad \heartsuit \cup \spadesuit \]
LTL Semantics

Let $\sigma = \sigma_0\sigma_1\sigma_2\sigma_3\sigma_4\sigma_5 \ldots$ be a behaviour. Then define notation:

- $\sigma|_0 = \sigma$
- $\sigma|_1 = \sigma_1\sigma_2\sigma_3\sigma_4\sigma_5 \ldots$
- $\sigma|_{n+1} = (\sigma|_1)|_n$
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Semantics

The models of LTL are behaviours. For atomic propositions, we just look at the first state. We often identify states with the set of atomic propositions they satisfy.

\[
\sigma \models p \iff p \in \sigma_0
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- $\sigma \models \varphi \land \psi \iff \sigma \models \varphi$ and $\sigma \models \psi$
- $\sigma \models \neg \varphi \iff \sigma \not\models \varphi$
- $\sigma \models \Diamond \varphi \iff \sigma|_1 \models \varphi$
- $\sigma \models \varphi \mathcal{U} \psi \iff$ There exists an $i$ such that $\sigma|i \models \psi$
  and for all $j < i$, $\sigma|j \models \varphi$

We say $P \models \varphi \iff \forall \sigma \in \llbracket P \rrbracket. \sigma \models \varphi$. 
Derived Operators

The operator $\Diamond \varphi$ ("finally" or "eventually") says that $\varphi$ will be true at some point.

The operator $\Box \varphi$ ("globally" or "always") says that $\varphi$ is always true from now on.

Exercise

- Give the semantics of $\Box$ and $\Diamond$.
- Define $\Box$ and $\Diamond$ in terms of other operators.
More Exercises

Let $\rho$ be this behaviour:

\[ \rho \mid = \spadesuit \]

\[ \rho \mid = \heartsuit \]

\[ \rho \mid = \diamondsuit \]

\[ \rho \mid = 3 \]

\[ \rho \mid = 3(\heartsuit \land \neg \diamondsuit) \]

\[ \rho \mid = 2(\heartsuit \land \diamondsuit) \]

\[ \rho \mid = U(\heartsuit \land \diamondsuit) \]

\[ \rho \mid = \cdots \]

\[ \rho \mid = \heartsuit ? \]
More Exercises

Let $\rho$ be this behaviour:

\[
\begin{align*}
\rho & \models \lozenge \text{?} \\
\rho & \models \spadesuit \text{?}
\end{align*}
\]

More Derived Operators

Define "Infinitely Often" in LTL.

Define "Almost Globally" in LTL (always true from some point onwards).
More Exercises

Let \( \rho \) be this behaviour:

\[
\begin{align*}
\rho &|= \heartsuit? \\
\rho &|= \spadesuit? \\
\rho &|= \bigcirc \spadesuit?
\end{align*}
\]
More Exercises

Let $\rho$ be this behaviour:

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\rho &|\models \diamondsuit \heartsuit?
\end{align*}
\]

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Let \( \rho \) be this behaviour:

\[ \begin{align*}
\rho |&= ♥?
\rho |&= ♠?
\rho |&= ◇?
\rho |&= ○ ♠?
\rho |&= ◊ ♥?
\rho|_3 |&= ◊ (♥ ∧ ¬♠)?
\end{align*} \]
More Exercises

Let $\rho$ be this behaviour:

\[\begin{align*}
&\heartsuit &\spadesuit &\heartsuit &\heartsuit\spadesuit &\heartsuit\spadesuit &\heartsuit\spadesuit &\ldots
\end{align*}\]

\[
\begin{align*}
\rho \models &\heartsuit? \\
\rho \models &\spadesuit? \\
\rho \models &\Diamond \spadesuit? \\
\rho \models &\Diamond \heartsuit? \\
\rho_{3} \models &\Diamond (\heartsuit \land \neg \spadesuit)? \\
\rho \models &\Diamond \Box (\heartsuit \land \spadesuit)?
\end{align*}
\]
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Let $\rho$ be this behaviour:

\[
\begin{align*}
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\rho |\models \heartsuit ? \\
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\rho |\models \Diamond \heartsuit ? \\
\rho|_3 |\models \Diamond (\heartsuit \land \neg \spadesuit) ? \\
\rho |\models \Diamond \Box (\heartsuit \land \spadesuit) ? \\
\rho |\models \Box (\heartsuit \mathcal{U} \spadesuit) ?
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More Exercises

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\[ \begin{align*}
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    \rho |\!\!\!\!\|= & \; \spadesuit \? \\
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    \rho |\!\!\!\!\|= & \; \Diamond \; \heartsuit \? \\
    \rho |3\!\!\!\!\|= & \; \Diamond \; (\heartsuit \land \neg \spadesuit) \? \\
    \rho |\!\!\!\!\|= & \; \Diamond \Diamond \; (\heartsuit \land \spadesuit) \? \\
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\end{align*} \]

More Derived Operators

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- Define “Almost Globally” in LTL (always true from some point onwards).
We can see that it is always possible for a run to move to the terminated state. How do we express this in LTL?
We can see that it is always possible for a run to move to the terminated state. How do we express this in LTL? We can't! — it is a branching time property.

**Branching Time**

Dealing with branching time properties requires a different logic called CTL (Computation Tree Logic). Learn about it in COMP3153/9153 or COMP6752.
A counting argument for mechanical aids

How many scenarios are there for a program with $n$ finite processes consisting of $m$ atomic actions each?
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\frac{(nm)!}{m!^n}
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<table>
<thead>
<tr>
<th>$n=2$</th>
<th>3</th>
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<tr>
<td>$m=2$</td>
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So, for 6 processes consisting of 6 sequential atomic actions each, that's merely $2^{670,177,736,637,149,247,308,800}$ scenarios. Do come back when you're done testing!
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Do come back when you’re done testing!
Sobering Conclusion

For any realistic concurrent program, it is *infeasible to test* all possible scenarios.

We need to apply smarter techniques than brute-force testing to establish properties of concurrent programs. *Formal methods* let us reason about programs, or, if that is too hard, about *abstractions* of programs.
Industrially applicable formal methods

To verify that program $P$ has property $\varphi$ (i.e. $P \models \varphi$), we can use:

- **model checking** — exhaustively searching through (an efficient representation of) $P$’s state space to find a counterexample to $\varphi$

- **theorem proving** — construct a (formal) proof of $\varphi$

To be relevant in practice, these techniques must be supported by tools.
Model Checking

Pros: easy to use push-button technology; instructive counter examples (error traces) help debugging

Cons: state (space) explosion problem
Model Checking

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Where can I learn more about model checking?
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**Answer**
COMP3153/9153 *Algorithmic Verification* (should run in T2)
(Interactive) Theorem Proving

**Pros:** no (theoretical) limits on state spaces

**Cons:** requires expert users (e.g. skilled computer scientists, mathematicians, or logicians) to hand-crank through proofs

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**Answer** COMP4161 Advanced Verification (should run in T3)
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**Answer**
COMP4161 *Advanced Verification* (should run in T3)
A model checker for concurrent systems with a lot of useful features and support for LTL model checking.

http://www.spinroot.com

Programs are modelled in the Promela language.
Promela in brief

- A kind of weird hybrid of C and Guarded Command Language.
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**Warning**

Variables of non-fixed size like *int* are of machine determined size, like C.
Example 1: Hello World

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Example 1: Hello World

Johannes will demonstrate the basics of proctype and run using some simple examples.

**Take-away**

You can use SPIN to *randomly simulate* Promela programs as well as model check them.
Example 2: Counters

Johannes will demonstrate a program that exhibits non-deterministic behaviour due to scheduling.
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Johannes will demonstrate a program that exhibits non-deterministic behaviour due to scheduling.

Explicit non-determinism

You can also add explicit non-determinism using if and do blocks:

```plaintext
if
:: (n % 2 != 0) -> n = 1;
:: (n >= 0) -> n = n - 2;
:: (n % 3 == 0) -> n = 3;
:: else -> skip;
fi
```
Example 2: Counters

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:: else -> skip;
fi
```

What would happen without the else line?
Guards

The arrows in the previous slide are just sugar for semicolons:

```
if
:: (n % 2 != 0); n = 1;
:: (n >= 0); n = n - 2;
:: (n % 3 == 0); n = 3;
fi
```

A boolean expression by itself forms a guard. Execution can only progress past a guard if the boolean expression evaluates to true (non-zero).

If the entire system cannot make progress, that is called deadlock. SPIN can detect deadlock in Promela programs.
mtype and Looping

mtype = \{RED, YELLOW, GREEN\};
active proctype TrafficLight() {
    mtype state = GREEN;
    do
    :: (state == GREEN) -> state = YELLOW;
    :: (state == YELLOW) -> state = RED;
    :: (state == RED) -> state = GREEN;
    od
}

Non-determinism can be avoided by making guards mutually exclusive. Exit loops with break.
### Volatile Variables

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>var</strong> y, z ← 0, 0</td>
<td></td>
</tr>
<tr>
<td>p₁: var x;</td>
<td>q₁: y ← 1;</td>
</tr>
<tr>
<td>p₂: x ← y + z;</td>
<td>q₂: z ← 2;</td>
</tr>
</tbody>
</table>

**Question**

What are the possible final values of \( x \)?

It is possible, as we cannot guarantee that the statement \( p₂ \) is executed atomically — that is, as one step. Typically, we require that each statement only accesses (reads from or writes to) at most one shared variable at a time. Otherwise, we cannot guarantee that each statement is one atomic step. This is called the **limited critical reference** restriction.
Volatile Variables

<table>
<thead>
<tr>
<th>var $y, z \leftarrow 0, 0$</th>
<th>$p_1$: var $x$;</th>
<th>$q_1$: $y \leftarrow 1$;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_2$: $x \leftarrow y + z$</td>
<td>$q_2$: $z \leftarrow 2$;</td>
<td></td>
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</table>

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What are the possible final values of $x$?

What about $x = 2$? Is that possible?
Volatile Variables

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Question

What are the possible final values of x?
What about x = 2? Is that possible?
It is possible, as we cannot guarantee that the statement p₂ is executed atomically — that is, as one step.

Typically, we require that each statement only accesses (reads from or writes to) at most one shared variable at a time. Otherwise, we cannot guarantee that each statement is one atomic step. This is called the limited critical reference restriction.
Ensuring Atomicity

We will often have multiple actions that we wish to group into one step, i.e. to execute **atomically**.

**Example (Counters)**

In our counter example, if each process executes the loop body atomically the result number can be guaranteed.

In Promela we can simply state this requirement, but in real programming languages we must use **synchronisation** techniques to achieve this.
Grouping statements in Promela with `atomic` prevents them from being interrupted.

If a statement in an atomic block is blocked, atomicity is temporarily suspended and another process may run.
**atomic and d_step**

Grouping statements with \texttt{d\_step} is more efficient than \texttt{atomic}, as it groups them all into \textbf{one transition}.

Non-determinism (\texttt{if,do}) is not allowed in \texttt{d\_step}. If a statement in the block \texttt{blocks}, a \texttt{runtime error} is raised.
Atomicity

In the Real World™, we don’t have the luxury of atomic and d_step blocks. To solve this for real systems, we need solutions to the critical section problem.
Atomicity

In the Real World™, we don’t have the luxury of atomic and \texttt{d-step} blocks. To solve this for real systems, we need solutions to the \textit{critical section problem}.

A sketch of the problem can be outlined as follows:

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{forever do} & \textbf{forever do} \\
\textit{non-critical section} & \textit{non-critical section} \\
\textit{pre-protocol} & \textit{pre-protocol} \\
\textit{critical section} & \textit{critical section} \\
\textit{post-protocol} & \textit{post-protocol} \\
\hline
\end{tabular}
\end{center}
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The non-critical section models the possibility that a process may do something else. It can take any amount of time (even infinite).
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In the Real World™, we don’t have the luxury of atomic and `d_step` blocks. To solve this for real systems, we need solutions to the critical section problem.

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</tr>
</tbody>
</table>

The non-critical section models the possibility that a process may do something else. It can take any amount of time (even infinite). Our task is to find a pre- and post-protocol such that certain atomicity properties are satisfied.
Desiderata

We want to ensure two main properties and two secondary ones:

- **Mutual Exclusion** No two processes are in their critical section at the same time.
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**Question**

Which is safety and which is liveness?

**Eventual Entry** is liveness, the rest are safety.
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Which is safety and which is liveness?
Eventual Entry is liveness, the rest are safety.
First Attempt

We can implement `await` using primitive machine instructions or OS syscalls, or even using a busy-waiting loop.

<table>
<thead>
<tr>
<th>var <code>turn ← 1</code></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>forever do</strong></td>
</tr>
<tr>
<td><code>p_1</code> <em>non-critical section</em></td>
</tr>
<tr>
<td><code>p_2</code> <code>await turn = 1;</code></td>
</tr>
<tr>
<td><code>p_3</code> <em>critical section</em></td>
</tr>
<tr>
<td><code>p_4</code> <code>turn ← 2</code></td>
</tr>
</tbody>
</table>

**Question**

Mutual Exclusion?
First Attempt

We can implement `await` using primitive machine instructions or OS syscalls, or even using a busy-waiting loop.

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</tr>
<tr>
<td>p₂</td>
<td>await turn = 1;</td>
</tr>
<tr>
<td>p₃</td>
<td>critical section</td>
</tr>
<tr>
<td>p₄</td>
<td>turn ← 2</td>
</tr>
<tr>
<td>q₁</td>
<td>non-critical section</td>
</tr>
<tr>
<td>q₂</td>
<td>await turn = 2;</td>
</tr>
<tr>
<td>q₃</td>
<td>critical section</td>
</tr>
<tr>
<td>q₄</td>
<td>turn ← 1</td>
</tr>
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Question

Mutual Exclusion? Yup!
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We can implement `await` using primitive machine instructions or OS syscalls, or even using a busy-waiting loop.

<table>
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<tr>
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<td>q₁  <code>non-critical section</code></td>
</tr>
<tr>
<td>p₂  <code>await turn = 1;</code></td>
<td>q₂  <code>await turn = 2;</code></td>
</tr>
<tr>
<td>p₃  <code>critical section</code></td>
<td>q₃  <code>critical section</code></td>
</tr>
<tr>
<td>p₄  <code>turn ← 2</code></td>
<td>q₄  <code>turn ← 1</code></td>
</tr>
</tbody>
</table>

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Mutual Exclusion? Yup!
Other criteria?
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<td>p₄ <code>turn ← 2</code></td>
</tr>
<tr>
<td>forever do</td>
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<tr>
<td>q₁ <code>non-critical section</code></td>
</tr>
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<tr>
<td>q₃ <code>critical section</code></td>
</tr>
<tr>
<td>q₄ <code>turn ← 1</code></td>
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Mutual Exclusion? Yup!
Other criteria? Nope!
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We can implement **await** using primitive machine instructions or OS syscalls, or even using a busy-waiting loop.

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<tr>
<td><strong>forever do</strong></td>
</tr>
<tr>
<td>p₁  <em>non-critical section</em></td>
</tr>
<tr>
<td>p₂  <strong>await</strong> turn = 1;</td>
</tr>
<tr>
<td>p₃  <strong>critical section</strong></td>
</tr>
<tr>
<td>p₄  turn ← 2</td>
</tr>
</tbody>
</table>

| **forever do** |
| q₁  *non-critical section* |
| q₂  **await** turn = 2; |
| q₃  **critical section** |
| q₄  turn ← 1 |

**Question**

Mutual Exclusion? **Yup!**
Other criteria? **Nope!** What if q₁ never finishes?
Second Attempt

```plaintext
var wantp, wantq ← False, False

<table>
<thead>
<tr>
<th>forever do</th>
<th>forever do</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_1: non-critical section</td>
<td>q_1: non-critical section</td>
</tr>
<tr>
<td>p_2: await wantq = False;</td>
<td>q_2: await wantp = False;</td>
</tr>
<tr>
<td>p_3: wantp ← True;</td>
<td>q_3: wantq ← True;</td>
</tr>
<tr>
<td>p_4: critical section</td>
<td>q_4: critical section</td>
</tr>
<tr>
<td>p_7: wantp ← False</td>
<td>q_7: wantq ← False</td>
</tr>
</tbody>
</table>
```

Mutual exclusion is violated if they execute in lock-step (i.e. p_1 q_1 p_2 q_2 p_3 q_3 etc.)
Second Attempt

<table>
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<tr>
<th>var</th>
<th>wantp, wantq ← False, False</th>
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<tbody>
<tr>
<td>forever do</td>
<td>forever do</td>
</tr>
<tr>
<td>p₁</td>
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<tr>
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</tr>
<tr>
<td>p₂</td>
<td>await wantq = False;</td>
</tr>
<tr>
<td>q₂</td>
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</tr>
<tr>
<td>p₃</td>
<td>wantp ← True;</td>
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<tr>
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<tr>
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<td>wantp ← False</td>
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<tr>
<td>q₇</td>
<td>wantq ← False</td>
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Mutual exclusion is violated if they execute in lock-step (i.e. p₁q₁p₂q₂p₃q₃ etc.)
Third Attempt

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<tbody>
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<td><strong>forever do</strong></td>
</tr>
<tr>
<td><strong>p1</strong>  non-critical section</td>
</tr>
<tr>
<td><strong>p2</strong>  wantp ← True;</td>
</tr>
<tr>
<td><strong>p3</strong>  await wantq = False;</td>
</tr>
<tr>
<td><strong>p4</strong>  critical section</td>
</tr>
<tr>
<td><strong>p7</strong>  wantp ← False</td>
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<tr>
<td><strong>forever do</strong></td>
</tr>
<tr>
<td><strong>q1</strong>  non-critical section</td>
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Now we have a deadlock (or stuck state) if they proceed in lock step.
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<td>p₄  critical section</td>
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<td>p₇  wantp ← False</td>
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<tr>
<td>forever do</td>
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Now we have a deadlock (or stuck state) if they proceed in lock step.
Fourth Attempt

<table>
<thead>
<tr>
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<th>wantp, wantq ← False, False</th>
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</thead>
<tbody>
<tr>
<td>forever do</td>
<td></td>
</tr>
<tr>
<td>p1</td>
<td>non-critical section</td>
</tr>
<tr>
<td>p2</td>
<td>wantp ← True;</td>
</tr>
<tr>
<td>p3</td>
<td>while wantq do</td>
</tr>
<tr>
<td>p4</td>
<td>wantp ← False;</td>
</tr>
<tr>
<td>p5</td>
<td>wantp ← True</td>
</tr>
<tr>
<td>p6</td>
<td>critical section</td>
</tr>
<tr>
<td>p7</td>
<td>wantp ← False</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>forever do</td>
<td></td>
</tr>
<tr>
<td>q1</td>
<td>non-critical section</td>
</tr>
<tr>
<td>q2</td>
<td>wantq ← True;</td>
</tr>
<tr>
<td>q3</td>
<td>while wantp do</td>
</tr>
<tr>
<td>q4</td>
<td>wantq ← False;</td>
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<tr>
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<td>critical section</td>
</tr>
<tr>
<td>q7</td>
<td>wantq ← False</td>
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</tbody>
</table>

We have replaced the deadlock with live lock (looping) if they continuously proceed in lock-step.
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<td></td>
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<td><strong>p2</strong></td>
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<td>wantp ← False;</td>
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<tr>
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<td>wantp ← True</td>
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<tr>
<td><strong>p6</strong></td>
<td>critical section</td>
<td>while wantp do</td>
</tr>
<tr>
<td><strong>p7</strong></td>
<td>wantp ← False</td>
<td>q4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>q5</td>
</tr>
</tbody>
</table>

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# Fifth Attempt

<table>
<thead>
<tr>
<th>forever do</th>
<th>forever do</th>
</tr>
</thead>
</table>
| **p₁** | *non-critical section*
| **p₂** | `wantp = True;`
| **p₃** | *while wantq do*
| **p₄** | *if turn = 2 then*
| **p₅** | `wantp ← False;`
| **p₆** | *await turn = 1;*
| **p₇** | `wantp ← True`
| **p₈** | *critical section*
| **p₉** | `turn ← 2`
| **p₁₀** | `wantp ← False`
| **q₁** | *non-critical section*
| **q₂** | `wantq = True;`
| **q₃** | *while wantp do*
| **q₄** | *if turn = 1 then*
| **q₅** | `wantq ← False;`
| **q₆** | *await turn = 2;*
| **q₇** | `wantq ← True`
| **q₈** | *critical section*
| **q₉** | `turn ← 1`
| **q₁₀** | `wantq ← False`
Reviewing this attempt

The fifth attempt (Dekker’s algorithm) works well except if the scheduler pathologically tries to run the loop at $q_3 \cdots q_7$ when $\text{turn} = 2$ over and over rather than run the process $p$ (or vice versa).

What would we need to assume to prevent this?
Reviewing this attempt

The fifth attempt (Dekker’s algorithm) works well except if the scheduler pathologically tries to run the loop at $q_3 \cdots q_7$ when $\text{turn} = 2$ over and over rather than run the process $p$ (or vice versa).

What would we need to assume to prevent this?

**Fairness**

The *fairness assumption* means that if a process can always make a move, it will eventually be scheduled to make that move.

With this assumption, Dekker’s algorithm is correct.
Expressing Fairness in LTL

Let enabled(\(\pi\)) and taken(\(\pi\)) be predicates true in a state iff an action \(\pi\) is enabled, resp., taken.

**Examples**

*Weak fairness* for action \(\pi\) is then expressible as:

\[
\Box(\Box\text{enabled}(\pi) \Rightarrow \Diamond\text{taken}(\pi))
\]

*Strong fairness* for action \(\pi\) is then expressible as:

\[
\Box(\Box\Diamond\text{enabled}(\pi) \Rightarrow \Diamond\text{taken}(\pi))
\]

Promela can assume weak fairness when checking models.
What now?

- Do the homework exercises and submit them before the Friday lecture.
- Assignment 0 (warm-up) will be out in W2. You have enough knowledge to start it, but not yet enough to finish it.
- Get spin (and ispin) working on your development environment (or use VLAB/ssh)