Temporal Logic:
The Lesser of Three Evils

Leslie Lamport
Microsoft Research
The evil that men do lives after them.

*Julius Caesar*, by William Shakespeare
Where I Started

Making sure my concurrent algorithms were right.

Proving the Correctness of Multiprocess Programs

(IEEE TSE, 1977)

Proved:

Safety Properties: Invariance

Liveness Properties: P, Q
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Safety Properties: Invariance

Liveness Properties: $P \leadsto Q$
My Introduction to Temporal Logic

In 1977–78, Susan Owicki started a little seminar on Amir's 1977 FOCS paper. It sounded like formal nonsense to me, but I attended anyway. I discovered that:

- It was simple: One primitive temporal operator
  \[ \Delta = \neg \neg \]
- It worked beautifully for liveness:
  \[ P \land Q \Delta = \neg (P \Rightarrow Q) \]

Eventually, Susan and I wrote *Proving Liveness Properties of Concurrent Programs* (TOPLAS, 1982).
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Specification

Around 1980, my colleagues and I started trying to write specifications. Instead of stating some properties about an algorithm, say exactly what it has to do. Write the properties an algorithm/system/protocol should have.
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We had been using an exogenous logic:
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\[ \models F \] (validity of \( F \)) depends on underlying system.

Just had to switch to an endogenous logic:

\[ \models S \models F \]
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System specified by temporal logic formula \( S \).
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System specified by temporal logic formula \( S \)

\[ \models F \text{ becomes } \models S \Rightarrow F \]
It Didn’t Work!

My colleagues spent days unsuccessfully trying to specify a FIFO queue. The reason was obvious: the simple logic of Amir’s 1977 paper was not expressive enough.

An arms race ensued. Who could invent the biggest, most powerful temporal logic?

I was not immune: TIMESETS — A New Method for Temporal Reasoning About Programs (in LNCS 131, 1981)
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The Real Problem

Writing a specification as a list of properties doesn't work. No one can understand the consequences of a list of properties.
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No one can understand the consequences of a list of properties.
An Example: Weak Memory Models

Typically specified by axioms.
Even their designers don't understand them.

The original Alpha memory specification model allowed this:

Initially:
\[ x = y = 0 \]

Process 1:
\[ \text{if } x = 23 \text{ then } y := 42 \]

Process 2:
\[ \text{if } y = 42 \text{ then } x := 23 \]

After execution:
\[ x = 23, \quad y = 42 \]
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Typically specified by axioms.

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The original Itanium memory specification document.

We wrote a TLA\(^+\) specification and used our tools to check the document’s tiny examples.

We found several errors.
An Example: Weak Memory Models

Typically specified by axioms.

Even their designers don’t understand them.

No one can figure out from a list of axioms what a tiny bit of concurrent code can do.
What works

Specify liveness with Amir's original temporal logic.

Specify safety by a state machine (abstract program).

How to do this in temporal logic:

Generalize Amir's temporal logic.

Don't add new temporal operators.

Do generalize elementary formulas from state predicates to transition predicates.

But that's another story.
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What is Evil About Temporal Logic

A fundamental rule of ordinary math: to prove $A \Rightarrow B$, we assume $A$ and prove $B$.

The Deduction Principle: $P \Rightarrow Q$

The deduction principle is not valid for temporal logic (and other modal logics).

For example, a basic rule of temporal logic asserts that if $P$ is true then it is always true.

$P \Rightarrow \Box P$
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\begin{align*}
\frac{P}{Q} \\
\frac{Q}{P \Rightarrow Q}
\end{align*}
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For example, a basic rule of temporal logic asserts that if \( P \) is true then it is always true.

\[
\begin{align*}
P \\
\hline
\Box P
\end{align*}
\]
From

\[
\frac{P}{Q} \quad \frac{Q}{P \Rightarrow Q}
\]
From

\[ \frac{P}{Q} \]

\[ \frac{P}{P \implies Q} \]

and

\[ \frac{P}{\square P} \]
From

\[
\begin{array}{c}
P \\
\hline \\
Q \\
\hline \\
P \Rightarrow Q
\end{array}
\]

and

\[
\begin{array}{c}
P \\
\hline \\
\Box P
\end{array}
\]

by substituting \( \Box P \) for \( Q \) we deduce

\[
P \Rightarrow \Box P
\]
From
\[
\begin{align*}
P & \quad Q \\
\hline
Q & \quad P \quad Q \\
\hline
P & \Rightarrow Q
\end{align*}
\]
and
\[
\begin{align*}
P & \\
\hline
\Box P & \\
\hline
\Box P
\end{align*}
\]
by substituting \( \Box P \) for \( Q \) we deduce
\[
P \Rightarrow \Box P
\]
which asserts that if \( P \) is true now then it is always true.
From

\[ P \ \frac{P}{\frac{Q}{Q}} \]

\[ P \Rightarrow Q \]

and

\[ P \ \frac{P}{\square P} \]

by substituting \( \square P \) for \( Q \) we deduce

\[ P \Rightarrow \square P \]

which asserts that if \( P \) is true now then it is always true.
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A logic that can confuse Martín is evil.
Temporal logic is modal because it has an implicit *time* variable.
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A solution: make time explicit.
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For example: $P \leadsto Q$ becomes $\forall t : (P(t) \Rightarrow \exists s \geq t : Q(s))$. 
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This makes formulas ugly and hard to understand.
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For example: $P \rightarrow Q$ becomes $\forall t : (P(t) \Rightarrow \exists s \geq t : Q(s))$.

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Trying to eliminate this is what led Amir to temporal logic.
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For example: $P \leadsto Q$ becomes $\forall t : (P(t) \Rightarrow \exists s \geq t : Q(s))$.

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Trying to eliminate this is what led Amir to temporal logic.
(He was inspired by Nissim Francez’s thesis.)
Use a programming logic.
Use a programming logic.

Some programming logics:

- Hoare Logic (Tony Hoare 1968)
- Dynamic Logic (Vaughan Pratt 1974)
- Weakest Preconditions (Edsger Dijkstra 1975)
- Action Systems (Ralph Back ∼1983)

What they have in common: programs appear in formulas of the “logic.”
Greater Evil #2

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Greater Evil #2

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Why are they evil?
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What they have in common:

- programs appear in formulas of the “logic”.

Why are they evil? First a digression.
We can derive Program 2 from Program 1 by substituting $p + q \mod 2$ for $x$.

Program 1:

```plaintext
initially x = 0
while TRUE do if x = 0 then Prod else Cons end if
x := x + 1 mod 2
end while
```

Program 2:

```plaintext
initially p = q = 0
Process 1: while TRUE do await p = q; Prod; p := p + 1 mod 2 end while
Process 2: while TRUE do await p \neq q; Cons; q := q + 1 mod 2 end while
```

Two-Phase Handshake, an important hardware protocol.
Program 1:

initially $x = 0$
We can derive Program 2 from Program 1 by substituting \( p + q \mod 2 \) for \( x \).

Program 1:

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while TRUE do if \( x = 0 \) then Prod else Cons end if;

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Program 2:

initially $p = q = 0$
Program 1:

\[
\text{initially } x = 0 \\
\text{while } \text{TRUE} \text{ do if } x = 0 \text{ then } \text{Prod} \text{ else } \text{Cons} \text{ end if; } \\
x := x + 1 \text{ mod } 2 \\
\text{end while}
\]

Program 2:

\[
\text{initially } p = q = 0 \\
\text{Process 1: while } \text{TRUE} \text{ do await } p = q ;
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Program 1:

initially $x = 0$

while TRUE do if $x = 0$ then Prod else Cons end if;
      $x := x + 1 \mod 2$
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Program 2:

initially $p = q = 0$

Process 1: while TRUE do await $p = q; Prod;$
We can derive Program 2 from Program 1 by substituting \( p + q \mod 2 \) for \( x \).

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  if $x = 0$ then Prod else Cons end if;
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Process 1: while TRUE do
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Two-Phase Handshake, an important hardware protocol
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**Program 1:**

initially \( x = 0 \)

while TRUE do if \( x = 0 \) then Prod else Cons end if;

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While TRUE do if $x = 0$ then Prod else Cons end if;

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We can derive Program 2 from Program 1 by substituting $p + q \mod 2$ for $x$. See festschrift for Willem-Paul de Roever.

Program 1:

- **initially** $x = 0$
- **while** TRUE **do**
  - if $x = 0$ then *Prod* else *Cons* end if;
  - $x := x + 1 \mod 2$
- **end while**

Program 2:

- **initially** $p = q = 0$
- Process 1: **while** TRUE **do**
  - await $p = q; \text{ Prod}; \ p := p + 1 \mod 2$
- **end while**

- Process 2: **while** TRUE **do**
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A derivation is a refinement proof run backwards.

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A derivation is a refinement proof run backwards.

Refinement is substitution.

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How do you substitute $p + q \mod 2$ for $x$ in a program?

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How do you substitute $p + q \mod 2$ for $x$ in a program?

It can’t be done.

Program 1:

- **initially** $x = 0$
- **while** TRUE **do** if $x = 0$ then **Prod** else **Cons** end if;
  
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Why Programming Logics are Evil

Substitution of an expression for a variable is a fundamental operation of mathematics.
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A logic that doesn’t permit substitution is evil.
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Program refinement is based on substitution.

A programming logic that doesn’t permit substitution is especially evil.

Refinement by substitution is not a problem with temporal logic.

Temporal logic is a lesser evil.
Temporal logic is the best way I know of to reason about systems.
A Necessary Evil

Temporal logic is the best way I know of to reason about systems—especially for liveness properties.
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Someone as good as Amir would not have done anything evil unless it was necessary.
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We are all grateful that he did it.
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I am grateful that I had the privilege of being his colleague.
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He was a great scientist and a wonderful human being.
Thank you.