

The Rise and Fall of Linear Temporal Logic

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Monadic Logic

Monadic Class: First-order logic with $=$ and monadic predicates – captures *sylogisms*.

- $(\forall x)P(x), (\forall x)(P(x) \rightarrow Q(x)) \models (\forall x)Q(x)$

[Löwenheim, 1915]: The Monadic Class is decidable.

- *Proof:* Bounded-model property – if a sentence is satisfiable, it is satisfiable in a structure of bounded size.
- *Proof technique:* quantifier elimination.

Monadic Second-Order Logic: Allow second-order quantification on monadic predicates.

[Skolem, 1919]: Monadic Second-Order Logic is decidable – via bounded-model property and quantifier elimination.

Question: What about $<$?

Nondeterministic Finite Automata

$$A = (\Sigma, S, S_0, \rho, F)$$

- **Alphabet:** Σ
- **States:** S
- **Initial states:** $S_0 \subseteq S$
- **Nondeterministic transition function:**
 $\rho : S \times \Sigma \rightarrow 2^S$
- **Accepting states:** $F \subseteq S$

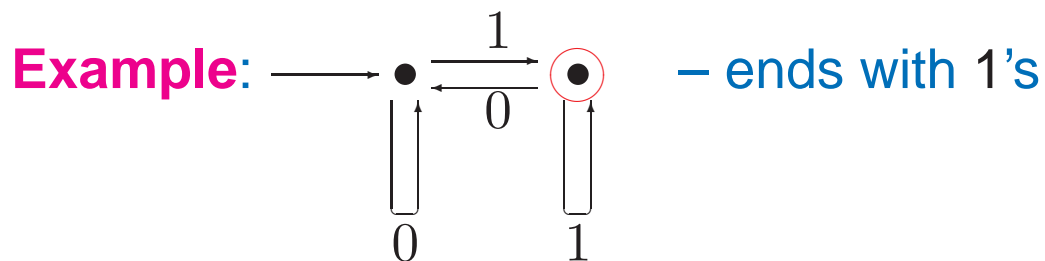
Input word: a_0, a_1, \dots, a_{n-1}

Run: s_0, s_1, \dots, s_n

- $s_0 \in S_0$
- $s_{i+1} \in \rho(s_i, a_i)$ for $i \geq 0$

Acceptance: $s_n \in F$

Recognition: $L(A)$ – words accepted by A .



Fact: NFAs define the class *Reg* of regular languages.

Logic of Finite Words

View finite word $w = a_0, \dots, a_{n-1}$ over alphabet Σ as a mathematical structure:

- Domain: $0, \dots, n - 1$
- Binary relation: $<$
- Unary relations: $\{P_a : a \in \Sigma\}$

First-Order Logic (FO):

- Unary atomic formulas: $P_a(x)$ ($a \in \Sigma$)
- Binary atomic formulas: $x < y$

Example: $(\exists x)((\forall y)(\neg(x < y)) \wedge P_a(x))$ – last letter is a .

Monadic Second-Order Logic (MSO):

- Monadic second-order quantifier: $\exists Q$
- New unary atomic formulas: $Q(x)$

NFA vs. MSO

Theorem [Büchi, Elgot, Trakhtenbrot, 1957-8 (independently)]: $\text{MSO} \equiv \text{NFA}$

- Both MSO and NFA define the class Reg.

Proof: Effective

- From NFA to MSO ($A \mapsto \varphi_A$)
 - Existence of run – existential monadic quantification
 - Proper transitions and acceptance - first-order formula
- From MSO to NFA ($\varphi \mapsto A_\varphi$): closure of NFAs under
 - *Union* – disjunction
 - *Projection* – existential quantification
 - *Complementation* – negation

NFA Nonemptiness

Nonemptiness: $L(A) \neq \emptyset$

Nonemptiness Problem: Decide if given A is nonempty.

Directed Graph $G_A = (S, E)$ of NFA $A = (\Sigma, S, S_0, \rho, F)$:

- **Nodes:** S
- **Edges:** $E = \{(s, t) : t \in \rho(s, a) \text{ for some } a \in \Sigma\}$

Lemma: A is nonempty iff there is a path in G_A from S_0 to F .

- Decidable in time linear in size of A , using *breadth-first search* or *depth-first search*.

MSO Satisfiability – Finite Words

Satisfiability: $models(\psi) \neq \emptyset$

Satisfiability Problem: Decide if given ψ is satisfiable.

Lemma: ψ is satisfiable iff A_ψ is nonempty.

Corollary: MSO satisfiability is decidable.

- Translate ψ to A_ψ .
- Check nonemptiness of A_ψ .

Complexity:

- *Upper Bound:* Nonelementary Growth

$$2^{\dots 2^n}$$

(tower of height $O(n)$)

- *Lower Bound* [Stockmeyer, 1974]: Satisfiability of FO over finite words is nonelementary (no bounded-height tower).

Sequential Circuits

Church, 1957: Use logic to specify sequential circuits.

Sequential circuits: $C = (I, O, R, f, g, R_0)$

- I : input signals
- O : output signals
- R : sequential elements
- $f : 2^I \times 2^R \rightarrow 2^R$: transition function
- $g : 2^R \rightarrow 2^O$: output function
- $R_0 \in 2^R$: initial assignment

Trace: element of $(2^I \times 2^R \times 2^O)^\omega$

$t = (I_0, R_0, O_0), (I_1, R_1, O_1), \dots$

- $R_{j+1} = f(I_j, R_j)$
- $O_j = g(R_j)$

Specifying Traces

View infinite trace $t = (I_0, R_0, O_0), (I_1, R_1, O_1), \dots$ as a mathematical structure:

- Domain: N
- Binary relation: $<$
- Unary relations: $I \cup R \cup O$

First-Order Logic (FO):

- Unary atomic formulas: $P(x)$ ($P \in I \cup R \cup O$)
- Binary atomic formulas: $x < y$

Example: $(\forall x)(\exists y)(x < y \wedge P(y))$ – P holds i.o.

Monadic Second-Order Logic (MSO):

- Monadic second-order quantifier: $\exists Q$
- New unary atomic formulas: $Q(x)$

Model-Checking Problem: Given circuit C and formula φ ; does φ hold in all traces of C ?

Easy Observation: Model-checking problem reducible to satisfiability problem – use FO to encode the “logic” (i.e., f, g) of the circuit C .

Büchi Automata

Büchi Automaton: $A = (\Sigma, S, S_0, \rho, F)$

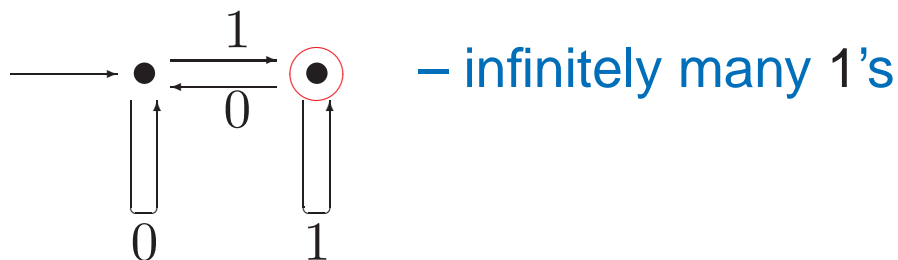
- *Alphabet:* Σ
- *States:* S
- *Initial states:* $S_0 \subseteq S$
- *Transition function:* $\rho : S \times \Sigma \rightarrow 2^S$
- *Accepting states:* $F \subseteq S$

Input word: a_0, a_1, \dots

Run: s_0, s_1, \dots

- $s_0 \in S_0$
- $s_{i+1} \in \rho(s_i, a_i)$ for $i \geq 0$

Acceptance: F visited infinitely often



Fact: Büchi automata define the class ω -Reg of ω -regular languages.

Logic vs. Automata II

Paradigm: Compile high-level logical specifications into low-level finite-state language

Compilation Theorem: [Büchi, 1960] Given an MSO formula φ , one can construct a Büchi automaton A_φ such that a trace σ satisfies φ if and only if σ is accepted by A_φ .

MSO Satisfiability Algorithm:

1. φ is satisfiable iff $L(A_\varphi) \neq \emptyset$
2. $L(\Sigma, S, S_0, \rho, F) \neq \emptyset$ iff there is a path from S_0 to a state $f \in F$ and a cycle from f to itself.

Corollary [Church, 1960]: Model checking sequential circuits wrt MSO specs is decidable.

Church, 1960: “Algorithm not very efficient” (*nonelementary complexity*, [Stockmeyer, 1974]).

Temporal Logic

Prior, 1914–1969, Philosophical Preoccupations:

- *Religion*: Methodist, Presbyterian, atheist, agnostic
- *Ethics*: “Logic and The Basis of Ethics”, 1949
- *Free Will, Predestination, and Foreknowledge*:
 - “The future is to some extent, even if it is only a very small extent, something we can make for ourselves”.
 - “Of what will be, it has now been the case that it will be.”
 - “There is a deity who infallibly knows the entire future.”

Mary Prior: “I remember his waking me one night [in 1953], coming and sitting on my bed, . . . , and saying he thought one could make a formalised tense logic.”

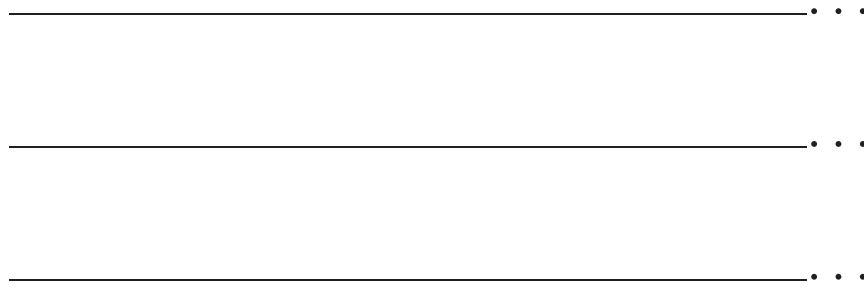
- 1957: “Time and Modality”

Linear vs. Branching Time, A

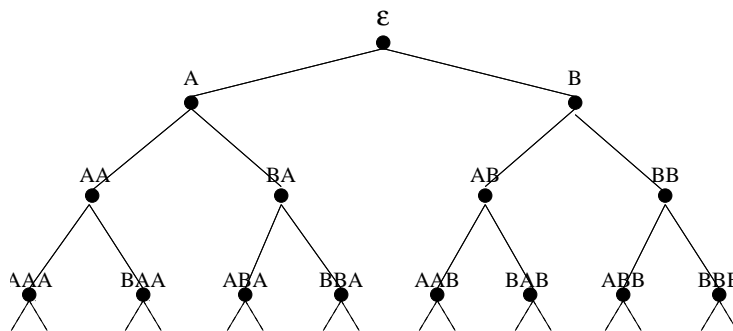
- Prior's first lecture on tense logic, Wellington University, 1954: linear time.
- Prior's "Time and modality", 1957: relationship between linear tense logic and modal logic.
- Sep. 1958, letter from Saul Kripke: "[I]n an indetermined system, we perhaps should not regard time as a linear series, as you have done. Given the present moment, there are several possibilities for what the next moment may be like – and for each possible next moment, there are several possibilities for the moment after that. Thus the situation takes the form, not of a linear sequence, but of a 'tree'". (Kripke was a high-school student, not quite 18, in Omaha, Nebraska.)

Linear vs. Branching Time, B

- **Linear time:** a system induces a set of traces
- **Specs:** describe traces



- **Branching time:** a system induces a trace tree
- **Specs:** describe trace trees



Linear vs. Branching Time, C

- Prior developed the idea into Ockhamist and Peircean theories of branching time (branching-time logic *without* path quantifiers)

Sample formula: $CKM_pM_qAMK_pM_qMK_qMp$

- Burgess, 1978: “Prior would agree that the determinist sees time as a line and the indeterminist sees times as a system of forking paths.”

Linear vs. Branching Time, D

Philosophical Conundrum

- Prior:

- Nature of course of time – branching
- Nature of course of events – linear

- Rescher:

- Nature of time – linear
- Nature of course of events – branching
- “We have ‘branching *in* time’, not ‘branching *of* time’”.

Linear time: Hans Kamp, Dana Scott and others continued the development of linear time during the 1960s.

Temporal and Classical Logics

Key Theorem:

- **Kamp, 1968:** Linear temporal logic with past and binary temporal connectives (“until” and “since”), over the integers, has precisely the expressive power of FO.

The Temporal Logic of Programs

Precursors:

- **Prior**: “There are practical gains to be had from this study too, for example in the representation of time-delay in computer circuits”
- **Rescher & Urquhart, 1971**: applications to processes (“a programmed sequence of states, deterministic or stochastic”)

“**Big Bang 1**” [Pnueli, 1977]:

- Future linear temporal logic (LTL) as a logic for the specification of non-terminating programs
- Temporal logic with “eventually” and “always” (later, with “next” and “until”)
- Model checking via reduction to MSO and automata

Crux: Need to specify *ongoing behavior* rather than *input/output relation*!

Linear Temporal Logic

Linear Temporal logic (LTL): logic of temporal sequences (Pnueli, 1977)

Main feature: time is implicit

- *next* φ : φ holds in the next state.
- *eventually* φ : φ holds eventually
- *always* φ : φ holds from now on
- φ *until* ψ : φ holds until ψ holds.

• $\pi, w \models \text{next } \varphi$ **if** $w \bullet \xrightarrow{\varphi} \bullet \xrightarrow{\quad} \bullet \xrightarrow{\quad} \bullet \dots$

• $\pi, w \models \varphi \text{ until } \psi$ **if** $w \bullet \xrightarrow{\varphi} \bullet \xrightarrow{\varphi} \bullet \xrightarrow{\varphi} \bullet \xrightarrow{\psi} \bullet \dots$

Examples

Psalm 34:14: “*Depart from evil and do good*”

- always not (CS_1 and CS_2): mutual exclusion (safety)
- always (Request implies eventually Grant): liveness
- always (Request implies (Request until Grant)): liveness

Expressive Power

- Gabbay, Pnueli, Shelah & Stavi, 1980: Propositional LTL over the naturals has precisely the expressive power of FO.
- Thomas, 1979: FO over naturals has the expressive power of star-free ω -regular expressions

Summary: LTL=FO=star-free ω -RE < MSO= ω -RE

Meyer on LTL, 1980, in “Ten Thousand and One Logics of Programming”:

“The corollary due to Meyer – I have to get in my controversial remark – is that that [GPSS’80] makes it theoretically uninteresting.”

Computational Complexity

Recall: Satisfiability of FO over traces is non-elementary

Contrast with LTL:

- Wolper, 1981: LTL satisfiability is in EXPTIME.
- Halpern&Reif, 1981, Sistla&Clarke, 1982: LTL satisfiability is PSPACE-complete.

Basic Technique: *tableau* (influenced by branching-time techniques)

PLTL

Lichtenstein, Pnueli, & Zuck, 1985: past-time connectives are useful in LTL:

- yesterday q : q was true in the previous state
- past p : q was true sometime in the past
- p since q : p has been true since q was true

Example: always ($rcv \rightarrow$ past snt)

Theorem

- Expressively equivalent to LTL [LPZ'85]
- Satisfiability of PLTL is PSPACE-complete [LPZ'85]
- PLTL is exponentially more succinct than LTL [Markey, 2002]

Model Checking

“Big Bang 2” [Clarke & Emerson, 1981, Queille & Sifakis, 1982]: Model checking programs of size m wrt CTL formulas of size n can be done in time mn .

Linear-Time Response [Lichtenstein & Pnueli, 1985]: Model checking programs of size m wrt LTL formulas of size n can be done in time $m2^{O(n)}$ (*tableau*-based).

Seemingly:

- *Automata*: Nonelementary
- *Tableaux*: exponential

Back to Automata

Exponential-Compilation Theorem:

[V. & Wolper, 1983–1986]

Given an LTL formula φ of size n , one can construct a Büchi automaton A_φ of size $2^{O(n)}$ such that a trace σ satisfies φ if and only if σ is accepted by A_φ .

Automata-Theoretic Algorithms:

1. LTL Satisfiability:

φ is satisfiable iff $L(A_\varphi) \neq \emptyset$ (PSPACE)

2. LTL Model Checking:

$M \models \varphi$ iff $L(M \times A_{\neg\varphi}) = \emptyset$ ($m2^{O(n)}$)

Vardi, 1988: Also with past.

Reduction to Practice

Practical Theory:

- Courcoubetis, V., Yannakakis & Wolper, 1989: Optimized search algorithm for explicit model checking
- Burch, Clarke, McMillan, Dill & Hwang, 1990: Symbolic algorithm for LTL compilation
- Clarke, Grumberg & Hamaguchi, 1994: Optimized symbolic algorithm for LTL compilation
- Gerth, Peled, V. & Wolper, 1995: Optimized explicit algorithm for LTL compilation

Implementation:

- Spin [Holzmann, 1995]: Promela w. LTL:
- SMV [McMillan, 1995]: SMV w. LTL

Satisfactory solution to Church's problem?
Almost, but not quite, since $LTL < MSO = \omega$ -RE.

Enhancing Expressiveness

- Wolper, 1981: Enhance LTL with grammar operators, retaining EXPTIME-ness (PSPACE [SC'82])
- V. & Wolper, 1983: Enhance LTL with automata, retaining PSPACE-completeness
- Sistla, V. & Wolper, 1985: Enhance LTL with 2nd-order quantification, losing elementariness
- V., 1989: Enhance LTL with fixpoints (as in Kozen's μ -calculus), retaining PSPACE-completeness

Bottom Line: ETL (LTL w. automata) = μ TL (LTL w. fixpoints) = MSO, and has exponential-compilation property.

Dynamic and Branching-Time Logics

Dynamic Logic [Pratt, 1976]:

- The $\Box\varphi$ of modal logic can be taken to mean “ φ holds after an execution of a program step”.
- Dynamic modalities:
 - $[\alpha]\varphi$ – φ holds after all executions of α .
 - $\psi \rightarrow [\alpha]\varphi$ corresponds to Hoare triple $\{\psi\}\alpha\{\varphi\}$.

Propositional Dynamic Logic [Fischer & Ladner, 1977]: *Boolean* propositions, programs – *regular expressions over atomic* programs.

Satisfiability [Pratt, 1978]: EXPTIME – using *tableau*-based algorithm

Extensions to nonterminating programs [Streett 1981, Harel & Sherman 1981, Kozen 1982] – less suitable for temporal properties.

Branching-Time Logic

From dynamic logic back to temporal logic:

The dynamic-logic view is clearly branching; what is the analog for temporal logic?

- Emerson & Clarke, 1980: correctness properties as fixpoints over computation trees
- Ben-Ari, Manna & Pnueli, 1981: branching-time logic UB; satisfiability in EXPTIME using tableaux
- Clarke & Emerson, 1981: branching-time logic CTL; efficient model checking
- Emerson & Halpern, 1983: branching-time logic CTL* – ultimate branching-time logic

Key Idea: Prior missed *path quantifiers*

- \forall eventually p : on all possible futures, p eventually happen.

Linear vs. Branching Temporal Logics

- **Linear time:** a system generates a set of computations
- **Specs:** describe computations
- **LTL:** $\textit{always}(\text{request} \rightarrow \textit{eventually grant})$

- **Branching time:** a system generates a computation tree
- **Specs:** describe computation trees
- **CTL:** $\forall \textit{always}(\text{request} \rightarrow \forall \textit{eventually grant})$

Combining Dynamic and Temporal Logics

Two distinct perspectives:

- Temporal logic: *state based*
- Dynamic logic: *action based*

Symbiosis:

- Harel, Kozen & Parikh, 1980: Process Logic (branching time)
- V. & Wolper, 1983: Yet Another Process Logic (branching time)
- Harel and Peleg, 1985: Regular Process Logic (linear time)
- Henriksen and Thiagarajan, 1997: Dynamic LTL (linear time)

Tech Transfer:

- Beer, Ben-David & Landver, IBM, 1998: RCTL (branching time)
- Beer, Ben-David, Eisner, Fisman, Gringauze, Rodeh, IBM, 2001: Sugar (branching time)

From LTL to PSL

Model Checking at Intel

Prehistory:

- 1990: successful feasibility study using Kurshan's COSPAN
- 1992: a pilot project using CMU's SMV
- 1995: an internally developed (linear time) property-specification language

History:

- 1997: Development of 2nd-generation technology started (engine and language)
- 1999: BDD-based model checker released
- 2000: SAT-based model checker released
- 2000: *ForSpec* (language) released

Dr. Vardi Goes to Intel

1997: (w. Fix, Hadash, Kesten, & Sananes)

V.: How about LTL?

F., H., K., & S.: Not expressive enough.

V.: How about ETL? μ TL?

F., H., K., & S.: Users will object.

1998 (w. Landver)

V.: How about ETL?

L.: Users will object.

L.: How about regular expressions?

V.: They are equivalent to automata!

RELTL: LTL plus dynamic modalities,
interpreted linearly – $[e]\varphi$

E.g.: $[\text{true}^*, \text{send}, \text{!cancel}]\text{sent}$

Easy: RELTL=ETL= ω -RE

ForSpec: RELTL + hardware features (clocks and resets) [Armoni, Fix, Flaisher, Gerth, Ginsburg, Kanza, Landver, Mador-Haim, Singerman, Tiemeyer, V., Zbar]

From ForSpec to PSL

Industrial Standardization:

- Process started in 2000
- Four candidates: IBM's Sugar, Intel's ForSpec, Motorola's CBV, and Verisity's E.
- Fierce debate on linear vs. branching time

Outcome:

- Big political win for IBM (see references to PSL/Sugar)
- Big technical win for Intel
 - PSL is LTL + RE + clocks + resets
 - Branching-time extension as an acknowledgement to Sugar
 - Some evolution over time in hardware features
- Major influence on the design of **SVA** (another industrial standard)

Bottom Line: *Huge* push for model checking in industry.

What about the Past?

- Avoided in industrial languages due to implementation challenges
- Less important in model checking; if past events are important, then program would keep track of them.
- But, the past is important in specification (LPZ'85)!

Dax, Klaedtke, & Lange, 2010 (cf., Leucker & Sánchez, 2010): *Regular Temporal Logic* (RTL)

- PLTL
- Dynamic modalities: $[e]\varphi$
- Past Dynamic modalities: $[e]^{-}\varphi$

Theorem [DKL'10]

- Expressively equivalent to RELTL.
- Exponentially more succinct than RELTL.
- Satisfiability is PSPACE-complete

Linear Dynamic Logic (LDL)

Observations:

- Dynamic modalities subsume temporal connectives, e.g., $\text{always } q$ is equivalent to $[\text{true}^*]q$
- To capture past, add *reverse* operator to REs.
 - a : “consume” a and move forward.
 - a^- : “consume” a and move backward.

Inspiration:

- PDL+converse [Pratt, 1976]
- Two-way navigation in XPath

Example: $[\text{true}^*, \text{rcv}] \langle (\text{true}^-)^* \rangle \text{sent}$

Theorem:

- Expressively equivalent to RELTL.
- Exponentially more succinct than RELTL.
- Satisfiability is PSPACE-complete.

LTL is Dead, Long Live LDL!

What was important about PLTL?

- Linear time
- Simple syntax
- Exponential-compilation property
- *Equivalence to FO*

What is important about LDL?

- Linear time
- Extremely simple syntax: REs (with *reverse*) and dynamic modalities
- Exponential-compilation property
- *Equivalence to MSO*

Also: easy to pronounce :-)