

Logica temporale

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Testing e Verifica del Software AA 2526

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TESTO DI RIFERIMENTO: M.R.A. Ruth, M.D. Ryan Logic in Computer Science Modelling and Reasoning about systems - Capitolo 3 - allegato a questi appunti

- There is a great advantage in being able to verify the correctness of computer systems, whether they are hardware, software, or a combination. This is most obvious in the case of safety-critical systems, but also applies to those that are commercially critical, such as mass-produced chips, mission critical, etc.
 - Formal verification methods have quite recently become usable by industry and there is a growing demand for professionals able to apply them.
 - We study a fully automatic way to perform formal verification
 - not rule-based
 - called **model checking**

- Le tecniche di verifica formale sono generalmente viste come la somma di tre componenti:
 - Un framework in cui modellare il sistema che vogliamo analizzare
 - Un linguaggio di specifica delle proprietà da verificare
 - Un metodo per verificare che il sistema soddisfi le proprietà specificate.
 - Solitamente il Model Checking si basa sull'utilizzo di una logica temporale. Quindi, le tre componenti possono essere costituite come segue:
 - Si costruisce un modello M che descrive il comportamento del sistema
 - Si codifica la proprietà da verificare in una formula temporale ϕ
 - Si chiede al model checker di verificare che $M \models \phi$

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- Esistono diverse logiche temporali che possono essere divise in due classi fondamentali:
 - le linear-time logics (LTL) e le branching-time logics (CTL).
 - LTL considera il tempo come un insieme di cammini, dove cammino é una sequenza di istanti di tempo
 - CTL rappresenta il tempo come un albero, con radice l'istante corrente
 - Un'altra classificazione divide tra tempo continuo e discreto. Noi studieremo solo logiche discrete e senza metrica.

The aim of logic in computer science is to develop languages to model the situations we encounter as computer science professionals, in such a way that we can reason about them formally. Reasoning about situations means constructing arguments about them; we want to do this formally, so that the arguments are valid and can be defended rigorously, or executed on a machine. Consider the following argument:

Example 1.1

If the train arrives late and there are no taxis at the station, then John is late for his meeting. John is not late for his meeting. The train did arrive late. Therefore, there were taxis at the station.

The aim of logic in computer science is to develop languages to model the situations we encounter as computer science professionals, in such a way that we can reason about them formally. Reasoning about situations means constructing arguments about them; we want to do this formally, so that the arguments are valid and can be defended rigorously, or executed on a machine. Consider the following argument:

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Valid argument

Intuitively, the argument is valid, since if we put the first sentence and the third sentence together, they tell us that if there are no taxis, then John will be late. The second sentence tells us that he was not late, so it must be the case that there were taxis.

Another example

Example 1.2 If it is raining and Jane does not have her umbrella with her, then she will get wet. Jane is not wet. It is raining. Therefore, Jane has her umbrella with her.

Valid argument

Intuitively, the argument is valid, since if we put the first sentence and the third sentence together, they tell us that if there are no taxis, then John will be late. The second sentence tells us that he was not late, so it must be the case that there were taxis.

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Example 1.2 If it is raining and Jane does not have her umbrella with her, then she will get wet. Jane is not wet. It is raining. Therefore, Jane has her umbrella with her.

Example 1.1	Example 1.2
the train is late	it is raining
there are taxis at the station	Jane has her umbrella with her
John is late for his meeting	Jane gets wet.

The argument in each example could be stated without talking about trains and rain, as follows:
If p and not q , then r . Not r . p . Therefore, q .

The language we begin with is the language of propositional logic. It is based on propositions, or declarative sentences which one can, in principle, argue as being true or false.

- 1 The sum of the numbers 3 and 5 equals 8.
- 2 Jane reacted violently to Jack's accusations.
- 3 Every even natural number >2 is the sum of two prime numbers.
- 4 All Martians like pepperoni on their pizza.
- 5 Albert Camus ´etait un ´crivain fran,cais.
- 6 Die W"urde des Menschen ist unantastbar.

NOT Declarative sentences

The kind of sentences we won't consider here are non-declarative ones, like

- Could you please pass me the salt?
- Ready, steady, go!
- May fortune come your way.

Our strategy is to consider certain declarative sentences as being *atomic*, or *indecomposable*, like the sentence

‘The number 5 is even.’

We assign certain distinct symbols p , q , r , . . . , or sometimes p_1 , p_2 , p_3 , . . . to each of these atomic sentences and we can then code up more complex sentences in a compositional way.

For example, given the atomic sentences

p : ‘I won the lottery last week.’

q : ‘I purchased a lottery ticket.’

r : ‘I won last week’s sweepstakes.’

we can form more complex sentences according to the rules below:

- ¬ The negation of p is denoted by $\neg p$ and expresses 'I did not win the lottery last week,' or equivalently 'It is not true that I won the lottery last week.'
- ∨ Given p and r at least one of them is true: 'I won the lottery last week, or I won last week's sweepstakes;' we denote this by $p \vee r$ and call it the disjunction of p and r .
- ∧ Dually, the formula $p \wedge r$ denotes the conjunction of p and r : 'Last week I won the lottery and the sweepstakes.'

→ 'If I won the lottery last week, then I purchased a lottery ticket.' expresses an implication between p and q , suggesting that q is a logical consequence of p . We write $p\beta q$ for that. We call p the assumption of $p\beta q$ and q its conclusion.

Note that the implication is equally true whenever the assumption p is false regardless the value of the conclusion q .

\longleftrightarrow 'If and only if it is Sunday, I'm happy' expresses an equivalence between p and q , suggesting that q is a logical consequence of p and also p is a logical consequence of q . We write $p \longleftrightarrow q$ for that.

Nota che alcune volte usare \leftrightarrow è più completo che usare la semplice implicazione \rightarrow .

Ad esempio se ho un metodo `isPositive(x)` che restituisce vero se x è positivo e false se non lo è, allora la completa caratterizzazione del metodo è $x > 0 \leftrightarrow \text{isPositive}(x)$. Se scrivessi solo $x > 0 \rightarrow \text{isPositive}(x)$ allora con x negativo il metodo sarebbe libero di ritornare quello che vuole (true o false).

- La logica è costruita su di un insieme di formule atomiche **AP** $\{p, q, r, \dots\}$ che rappresentano descrizioni atomiche del sistema
 - Definiamo in maniera ricorsiva le formule LTL:
 - come la logica proposizionale (1) ($|$ significa “oppure”) - in stile come grammatica BNF

$$\phi ::= \top | \perp | p \in AP | \neg\phi | \phi \wedge \phi | \phi \vee \phi | \phi \rightarrow \phi |$$

- \top, \perp sono vero e falso
- $\neg, \wedge, \vee, \rightarrow$ sono connettivi logici classici

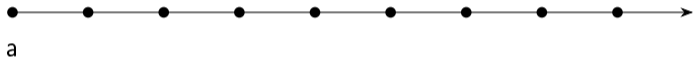
- Inseriamo operatori temporali (2):

$$\phi ::= \top \mid \perp \mid p \in AP \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \phi \rightarrow \phi \mid \\ X\phi \mid F\phi \mid G\phi \mid \phi U\phi \mid \phi W\phi \mid \phi R\phi$$

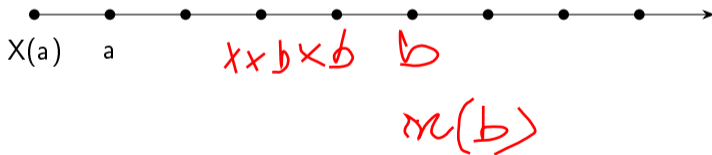
- X, F, G, U, W, R sono **connettivi temporali**
 - In particolare: X, F, G sono unari:
 - X means 'neXt state,'
 - F means 'some Future state,' and
 - G means 'all future states (Globally).'
 - The next three, U, R and W sono binari e sono 'Until,' 'Release' and 'Weak-until' respectively.

Significato intuitivo degli operatori

- se non uso operatori, si intende l'istante corrente. Esempio a:

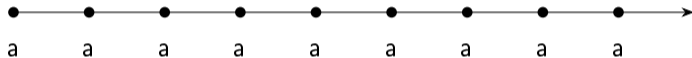


- X a: a è vero nell'istante successivo



Significato intuitivo degli operatori

- $G a$: a è vero sempre

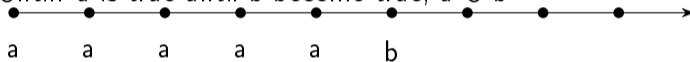


- $F a$: a è vero prima o poi

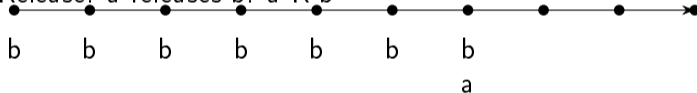


Alcuni esempi - Rappresentazione grafica

- Until: a is true until b become true, $a U b$



- Release: a releases b: $a R b$



The unary connectives (consisting of \neg and the temporal connectives X , F and G) bind most tightly. Next in the order come U , R and W ; then come \wedge and \vee ; and after that comes \rightarrow .

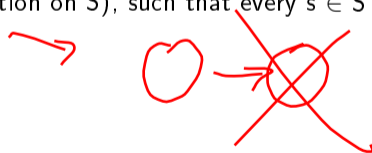
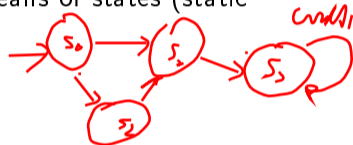
- **Esercizio:** alcuni esempi di LTL con e senza parentesi

- The kinds of systems we are interested in verifying using LTL may be modeled as transition systems. A transition system models a system by means of states (static structure) and transitions (dynamic structure).

A transition system $M = (S, s_0, \rightarrow, L)$ is

- a set of states S endowed
- a state is the initial state s_0
- with a transition relation \rightarrow (a binary relation on S), such that every $s \in S$ has some $s' \in S$ with $s \rightarrow s'$, and
- a labelling function $L : S \rightarrow \mathcal{P}(AP)$

I transition system sono i nostri *modelli*.

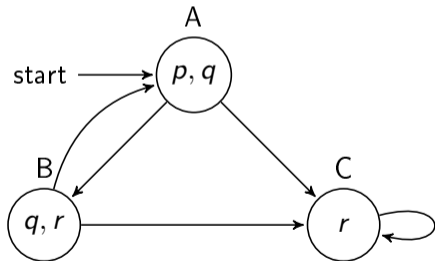


- a labelling function $L : S \rightarrow \mathcal{P}(AP)$
 $\mathcal{P}(AP)$ è il powerset – l'insieme delle parti – di proposizioni atomiche (**AP**)
 - L is that it is just an assignment of truth values to all the propositional atoms, as it was the case for propositional logic (we called that a valuation)
 - The difference now is that we have more than one state, so this assignment depends on which state s the system is in: $L(s)$ contains all atoms which are true in state s .

Graphical representation

- all the information about a (finite) transition system M can be expressed using directed graphs whose nodes (which we call states) contain all propositional atoms that are true in that state.

Example: M has only three states A , B , and C . The atomic propositions $AP = \{p, q, r\}$. The only possible transitions are $A \rightarrow B$, $A \rightarrow C$, $B \rightarrow A$, $B \rightarrow C$ and $C \rightarrow C$; and if $L(A) = \{p, q\}$, $L(B) = \{q, r\}$ and $L(C) = \{r\}$:



path: $A, B, A, C, C, C, C, \dots$

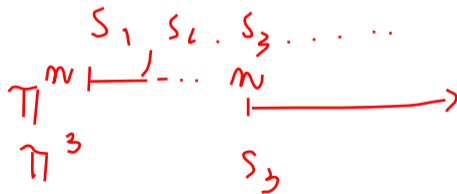
~~A, A, A, C, A, B~~

- The requirement in Definition that for every $s \in S$ there is at least one $s' \in S$ such that $s \rightarrow s'$ means that no state of the system can 'deadlock.'
 - This is a technical convenience, and in fact it does not represent any real restriction on the systems we can model. If a system did deadlock, we could always add an extra state sd representing deadlock,

- un esempio di deadlock



- A **path** in a model $M = (S, \rightarrow, L)$ is an infinite sequence of states s_1, s_2, s_3, \dots in S such that, for each $i \geq 1$, $s_i \rightarrow s_{i+1}$.
 - We write the path as $s_1 \rightarrow s_2 \rightarrow \dots$.
 - We write π^i for the suffix starting at s_i , e.g., π^3 is $s_3 \rightarrow s_4 \rightarrow \dots$.
 - Esempio



- $A \rightarrow B \rightarrow A \rightarrow B \rightarrow C \dots$
 - altri esempi

Validità di una formula LTL su un path (prop)

Definition

Let $M = (S, \rightarrow, L)$ be a model and $\pi = s_1 \rightarrow \dots$ be a **path** in M . Whether π satisfies an LTL formula is defined by the satisfaction relation \models as follows:

- 1 $\pi \models \top$
- 2 $\pi \not\models \perp$
- 3 $\pi \models p$ iff $p \in L(s_1)$
- 4 $\pi \models \neg\varphi$ iff $\pi \not\models \varphi$
- 5 $\pi \models \varphi_1 \wedge \varphi_2$ iff $\pi \models \varphi_1$ and $\pi \models \varphi_2$
- 6 $\pi \models \varphi_1 \vee \varphi_2$ iff $\pi \models \varphi_1$ or $\pi \models \varphi_2$
- 7 $\pi \models \varphi_1 \rightarrow \varphi_2$ iff $\pi \models \varphi_2$ whenever $\pi \models \varphi_1$

$\pi \not\models \phi$

Definition

Let $M = (S, \rightarrow, L)$ be a model and $\pi = s_1 \rightarrow \dots$ be a path in M . Whether π satisfies an LTL formula is defined by the satisfaction relation \models as follows:

- 8 $\pi \models X \varphi$ iff $\pi^2 \models \varphi$
- 9 $\pi \models G \varphi$ iff, for all $i \geq 1$, $\pi^i \models \varphi$
- 10 $\pi \models F \varphi$ iff there is some $i \geq 1$ such that $\pi^i \models \varphi$

Validità di una formula LTL (time 2)



- 11 **(Until)** $\pi \models a U b$ iff there is some $i \geq 1$ such that $\pi^i \models b$ and for all $j = \underline{1}, \dots, \underline{i-1}$ we have $\pi^j \models a$
- 12 **(Weak Until)** $\pi \models a W b$ iff either there is some $i \geq 1$ such that $\pi^i \models b$ and for all $j = 1, \dots, i-1$ we have $\pi^j \models a$; or for all $k \geq 1$ we have $\pi^k \models a$
- U, which stands for 'Until,' is the most commonly encountered one of these. The formula $a U b$ holds on a path if it is the case that a holds continuously until b holds. Moreover, a U b actually demands that b does hold in some future state.
 - Weak-until is just like U, except that $a W b$ does not require that b is eventually satisfied along the path in question, which is required by $a U b$.

No

- 13 **(Release)** $\pi \models a R b$ iff either there is some $i \geq 1$ such that $\pi^i \models a$ and for all $j = 1, \dots, i$ we have $\pi^j \models b$, or for all $k \geq 1$ we have $\pi^k \models b$.
- It is called 'Release' because its definition determines that b must remain true up to and including the moment when a becomes true (if there is one); a 'releases' b .
 - Release R is the dual of U ; that is, $a R b$ is equivalent to $\neg(\neg a U \neg b)$.

- Quando una formula è **valida** per una macchina M (e non solo per un path) ?

Definition

Suppose $M = (S, \rightarrow, L)$ is a model, $s \in S$, and φ an LTL formula. We write $M, s \models \varphi$ if, for every execution path π of M starting at s , we have $p \models f$

Example

Figura 3.3 e figura 3.5, alcune formule

- Se la macchina M ha uno stato iniziale s_0
 - Quando una formula è **valida** per una macchina M (e non solo per un path da uno stato) ?

Definition

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- Se la macchina M ha un insieme di stati iniziali S_0
 - Quando una formula è **valida** per una macchina M (e non solo per un path) ?

Definition

Suppose $M = (S, S_0, \rightarrow, L)$ is a model, $S_0 \subseteq S$ gli stati iniziali, and φ an LTL formula. We write $M \models \varphi$ if per ogni $s_0 \in S_0$ vale $M, s_0 \models \varphi$

Practical Pattern of specifications

- Safety properties:

- something is always true $G\phi$
 - something bad never happens $G\neg\phi$,

- Liveness properties:

- something will happen $F\phi$
- something good keeps happening ($GF\psi$ or $G(\phi \rightarrow F\psi)$)
- Esempi più complessi - 3.2

promise is true $\Rightarrow S$

$G(\text{promise} \Rightarrow S)$

$G(\neg \dots)$ non deve mai

$G(\neg \text{red})$

$F(\text{new})$ ~~$\neg G(\text{new})$~~

Important equivalences between LTL formulas

$$\neg (\varphi \wedge \psi) = \neg \varphi \vee \neg \psi$$

We say that two LTL formulas φ and ψ are semantically equivalent, or simply equivalent, writing $\varphi \equiv \psi$, if for all models M and all paths π in M : $\pi \models \varphi$ iff $\pi \models \psi$.

- solite equivalenze di and, or, not

Until e weak until

A weak until binary operator, denoted W , with semantics similar to that of the until operator but the stop condition is not required to occur (similar to release).

- $\varphi W \psi \equiv (\varphi U \psi) \vee G \varphi$

Both U and R can be defined in terms of the weak until:

- Until and Weak until: $\varphi U \psi \equiv \varphi W \psi \wedge F \psi$

Also R can be defined in terms of W

- $\varphi W \psi \equiv (\varphi U \psi) \vee G \varphi \equiv \varphi U (\psi \vee G \varphi) \equiv \psi R (\psi \vee \varphi)$
 $\varphi U \psi \equiv F \psi \wedge (\varphi W \psi)$
 $\varphi R \psi \equiv \psi W (\psi \wedge \varphi)$

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- $\varphi W \psi \equiv (\varphi U \psi) \vee G \varphi \equiv \varphi U (\psi \vee G \varphi) \equiv \psi R (\psi \vee \varphi) \quad \varphi U \psi \equiv F\psi \wedge (\varphi W \psi) \quad \varphi R \psi \equiv \psi W (\psi \wedge \varphi)$

F and G duality

$$\neg G(\text{red}) \equiv F(\neg \text{red})$$

$$G(\neg \text{white}) \equiv \neg F(\text{white})$$

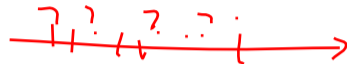
- F and G are duals:

- $\neg G \varphi \equiv F \neg \varphi$

- X is dual of itself: $\neg X \varphi \equiv X \neg \varphi$

- U and R are duals of each other:

- $\neg (\varphi U \psi) \equiv \neg \varphi R \neg \psi$



$$\neg F \varphi \equiv G \neg \varphi$$

$$\neg (\varphi R \psi) \equiv \neg \varphi U \neg \psi$$

$$\neg X \text{ deriv} = X \neg \text{deriv}$$

- F and G are duals:

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$$\neg F \varphi \equiv G \neg \varphi$$

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- U and R are duals of each other:

- $\neg (\varphi U \psi) \equiv \neg \varphi R \neg \psi$

$$\neg (\varphi R \psi) \equiv \neg \varphi U \neg \psi$$

↗

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- $\neg G \varphi \equiv F \neg \varphi$

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- U and R are duals of each other:

- $\neg (\varphi U \psi) \equiv \neg \varphi R \neg \psi$

$$\neg F \varphi \equiv G \neg \varphi$$

$$\neg (\varphi R \psi) \equiv \neg \varphi U \neg \psi$$

$$F(\text{pensione} \vee \text{licenziato}) = F(\text{pensione}) \vee F(\text{licenziato})$$

$$F(\text{pensione} \wedge \text{medaglia}) \neq F(\text{pensione}) \wedge F(\text{medaglia})$$

- It's also the case that F distributes over \vee and G over \wedge , i.e.,

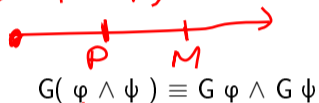
- $F(\varphi \vee \psi) \equiv F\varphi \vee F\psi$

- But F does not distribute over \wedge and G does not over \vee .

- F and G can be written as follows using U

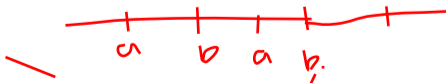
- $F\varphi \equiv \text{TU}\varphi$

$$G\varphi \equiv \perp R\varphi$$



$$G(\text{anno} \wedge \text{acciso}) = G(\text{anno}) \wedge G(\text{acciso})$$

$$G(a \vee b)$$



- It's also the case that F distributes over \vee and G over \wedge , i.e.,
 - $F(\varphi \vee \psi) \equiv F\varphi \vee F\psi$
 - But F does not distribute over \wedge and G does not over \vee .
 - F and G can be written as follows using U
 - $F\varphi \equiv \top U \varphi$

$$G(\varphi \wedge \psi) \equiv G\varphi \wedge G\psi$$

$$G\varphi \equiv \perp R \varphi$$

$$F \varphi = T U \varphi$$

- It's also the case that F distributes over \vee and G over \wedge , i.e.,

- $F(\varphi \vee \psi) \equiv F\varphi \vee F\psi$

$$G(\varphi \wedge \psi) \equiv G\varphi \wedge G\psi$$

- But F does not distribute over \wedge and G does not over \vee .

- F and G can be written as follows using U

- $F\varphi \equiv T U \varphi$

$$G\varphi \equiv \perp R \varphi$$

Adequate sets of connectives for LTL

Non tutti i connettivi sono necessari. Basterebbero di meno, ma per facilità nelle scritture delle formule li usiamo tutti.

Pattern of LTL properties

Esistono dei pattern pratici per la specifica mediante LTL di proprietà comuni:

<http://patterns.projects.cis.ksu.edu/documentation/patterns/ltl.shtml>

Alcune volte gli operatori si indicano così: G anche \square , F anche $\langle \rangle \diamond$

Absence – P is false:	
Globally	G (!P)
Before R	F R \rightarrow (!P U R)
After Q	G (Q \rightarrow G (!P))
Between Q and R	G ((Q & !R & F R) \rightarrow (!P U R))

Pattern (Existence)

Existence P becomes true :	
Globally	$F(P)$
(*) Before R	$!R \ W(P \ \& \ !R)$
After Q	$G(!Q) \ \ F(Q \ \& \ F P)$
(*) Between Q and R	$G(Q \ \& \ !R \ \rightarrow \ (!R \ W(P \ \& \ !R)))$
(*) After Q until R	$G(Q \ \& \ !R \ \rightarrow \ (!R \ U(P \ \& \ !R)))$

Pattern (Universality)

Universality P is true :	
Globally	$G (P)$
Before R	$F R \rightarrow (P \cup R)$
After Q	$G (Q \rightarrow G (P))$
Between Q and R	$G ((Q \ \& \ !R \ \& \ F R) \rightarrow (P \cup R))$
(*) After Q until R	$G (Q \ \& \ !R \rightarrow (P \cup R))$

- **Precedence** S precedes P
 - **Response** S responds to P :
 - **Precedence Chain** ...

Example: mutual exclusion

When concurrent processes share a resource (such as a file on a disk or a database entry), it may be necessary to ensure that they do not have access to it at the same time. Several processes simultaneously editing the same file would not be desirable
a process to access a critical resource must be in critical section

Safety Only one process is in its critical section at any time.

Liveness: Whenever any process requests to enter its critical section, it will eventually be permitted to do so.

Non-blocking: A process can always request to enter its critical section.

No strict sequencing: Processes need not enter their critical section in strict sequence.

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Safety Only one process is in its critical section at any time.

Liveness: Whenever any process requests to enter its critical section, it will eventually be permitted to do so.

Non-blocking: A process can always request to enter its critical section.

No strict sequencing: Processes need not enter their critical section in strict sequence.

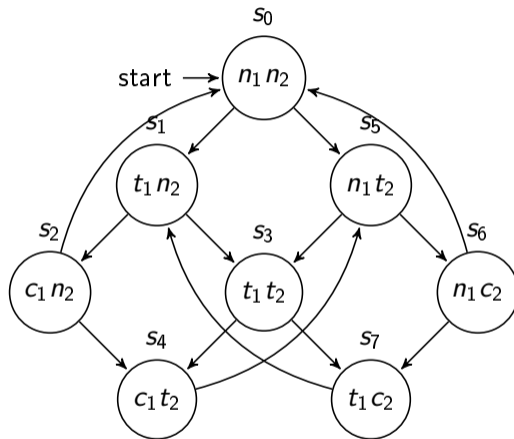


Figura: Every process can be in state: {non critical (n), trying to enter (t), critical state (c)}

Safety $G \neg (c1 \wedge c2)$. OK

Liveness: $G (t1 \rightarrow F c1)$. This is FALSE

Non-blocking: ... non riesco ad esprimerla in LTL

No strict sequencing: trovo un path in cui non c'è strict sequencing

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Safety $G \neg (c1 \wedge c2)$. OK

Liveness: $G (t1 \rightarrow F c1)$. This is FALSE

Non-blocking: ... non riesco ad esprimerla in LTL

No strict sequencing: trovo un path in cui non c'è strict sequencing

Ricorda la definizione:

Definition

Suppose M is a model, $s \in S$, and φ an LTL formula. We write $M, s \models \varphi$ if, for **every** execution path π of M starting at s , we have $p \models f$

- Quindi $M, s \models \mathbf{F}a$ vuol dire per ogni path a partire da s a accade
 - Come faccio a dire che non sempre accade in futuro ma *potrebbe* accadere?

COMPUTATION TREE LOGIC - CTL La CTL è una logica con connettivi che ci permette di specificare proprietà temporali.

- Essendo una logica branching-time, i suoi *modelli* sono rappresentabili mediante una struttura ad albero in cui il futuro non è deterministico: esistono differenti computazioni o paths nel futuro e uno di questi sarà il percorso realizzato.

Cosa è un modello per una logica proposizionale ???

- Un assegnamento di un valore di verità ad ogni proposizione
 - che rende vera la formula

- $a \vee b \wedge c$: trova un modello

- La logica è costruita su di un insieme di formule atomiche $AP \{p, q, r, \dots\}$ che rappresentano descrizioni atomiche del sistema

- Definiamo in maniera induttiva le formule CTL:

$$\phi ::= \top \mid \perp \mid p \in AP \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \phi \rightarrow \phi$$

- $\top, \perp, \neg, \wedge, \vee, \rightarrow$ sono connettivi logici classici

- Operatori temporali:

$$\phi ::= \begin{array}{ll} AX\phi | EX\phi & AF\phi | EF\phi \\ | A[\phi U \phi] | E[\phi U \phi] & AG\phi | EG\phi \end{array}$$

- $\top, \perp, \neg, \wedge, \vee, \rightarrow$ sono connettivi logici classici
- AX, EX, AG, EG, AU, EU, AF e EF sono **connettivi temporali**
- In particolare: A sta per "along All paths" (inevitably) E sta per "along at least (there Exists) one path" (possibly)
- X, F, G e U sono gli operatori della logica temporale lineare
 - Nota Bene: AU e EU sono operatori binari e i simboli X, F, G e U non possono occorrere se non preceduti da A o E e viceversa.

- Convenzione sull'ordinamento: gli operatori unary (AG, EG, AF, EF, AX, EX) legano con priorità più elevata, seguono gli operatori binary \wedge , \vee , e dopo ancora \longrightarrow , AU ed EU.
 - Esempi di formule CTL ben-formate
 - AG (q \longrightarrow EG r)
 - EF E(r U q)
 - A[p U EF r]
 - EF EG p \longrightarrow AF r

- Esempi di formule CTL non ben-formate
 - $EF G r$
 - $A!G!p$
 - $F[r U q]$
 - $EF(r U q)$
 - $AEF r$
 - $A[(r U q) /\ (p U r)]$

Definition

Let $M = (S, \rightarrow, L)$ be a model for CTL, s in S , φ a CTL formula. The relation $M, s \models \varphi$ is defined by structural induction on φ .

- If φ is atomic, satisfaction is determined by L .
 - If the top-level connective of φ is a boolean connective (\wedge , \vee , \neg , etc.) then the satisfaction question is answered by the usual truth-table definition and further recursion down φ .
 - If the top level connective is an operator beginning A , then satisfaction holds if all paths from s satisfy the 'LTL formula' resulting from removing the A symbol.
 - Similarly, if the top level connective begins with E , then satisfaction holds if some path from s satisfy the 'LTL formula' resulting from removing the E .

Non temporal formula are treated as usual

- 1 $M, s \models \top$
- 2 $M, s \not\models \perp$
- 3 $M, s \models p$ iff $p \in L(s)$
- 4 $M, s \models \neg\varphi$ iff $\pi M, s \not\models \varphi$
- 5 $M, s \models \varphi_1 \wedge \varphi_2$ iff $M, s \models \varphi_1$ and $M, s \models \varphi_2$
- 6 $M, s \models \varphi_1 \vee \varphi_2$ iff $M, s \models \varphi_1$ or $M, s \models \varphi_2$
- 7 $M, s \models \varphi_1 \rightarrow \varphi_2$ iff $M, s \models \varphi_2$ whenever $M, s \models \varphi_1$

$AP = \varphi, \psi$
 $AP' = \varphi, \top, \perp, \dots$

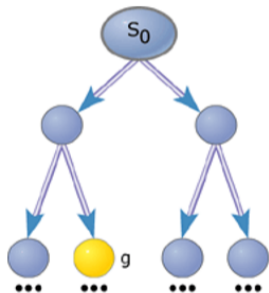
✓

Validità di una formula CTL (time)

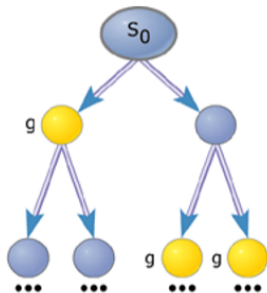
- 8 $M, s \models AX \varphi$ iff for all s_1 such that $s \rightarrow s_1$ we have $M, s_1 \models \varphi$
 - 9 $M, s \models EX \varphi$ iff some s_1 such that $s \rightarrow s_1$ we have $M, s_1 \models \varphi$
 - 10 $M, s \models AG \varphi$ iff, for all paths $s \rightarrow s_1 \rightarrow s_2 \dots$ and all s_i along the path, we have $M, s_i \models \varphi$
 - 11 $M, s \models EG \varphi$ iff, there is a path $s \rightarrow s_1 \rightarrow s_2 \dots$ and all s_i along the path, we have $M, s_i \models \varphi$
- AX: 'in every next state.'
 - EX: 'in some next state.'
 - AG: for All computation paths beginning in s the property φ holds Globally
 - EG: there Exists a path beginning in s such that φ holds Globally along the path.

- 12 $M, s \models \text{AF } \varphi$ iff, for all paths $s \rightarrow s_1 \rightarrow s_2 \dots$ there exists some s_i along the path, we have $M, s_i \models \varphi$
- 13 $M, s \models \text{EF } \varphi$ iff, there is a path $s \rightarrow s_1 \rightarrow s_2 \dots$ and for some s_i along the path, we have $M, s_i \models \varphi$
- AF: for All computation paths beginning in s there will be some Future state where φ holds.
 - EF: there Exists a computation path beginning in s such that φ holds in some Future state;

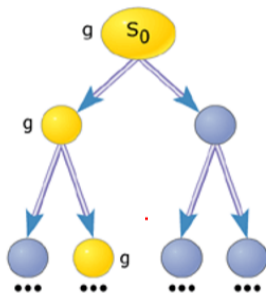
Validità di una formula CTL



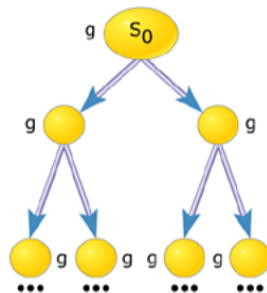
(a) EF g



(b) AF g



(c) EG g



(d) AG g

- 11 $M, s \models A[\phi_1 U \phi_2]$ iff, for all paths $s \rightarrow s_1 \rightarrow s_2 \dots$, that path satisfies $\phi_1 U \phi_2$ i.e., there is some s_i along the path, such that $M, s \models \phi_2$, and, for each $j < i$, we have $M, s \models \phi_1$.
- 12 $M, s \models E[\phi_1 U \phi_2]$ iff, there exists a path $s \rightarrow s_1 \rightarrow s_2 \dots$, that path satisfies $\phi_1 U \phi_2$.
 - A U All computation paths beginning in s satisfy that ϕ_1 Until ϕ_2 holds on it.
 - E U there Exists a computation path beginning in s such that ϕ_1 Until ϕ_2 holds on it.

Figura 3.3 e computation tree 3.5

- Se la macchina M ha un insieme di stati iniziali S_0
 - Quando una formula è **valida** per una macchina M (e non solo per un path) ?

Definition

Suppose $M = (S, S_0, \rightarrow, L)$ is a model, $S_0 \subseteq S$ gli stati iniziali, and φ an CTL formula. We write $M \models \varphi$ if per ogni $s_0 \in S_0$ vale $M, s_0 \models \varphi$

Pattern of CTL properties

Esistono dei pattern pratici per la specifica mediante CTL di proprietà comuni:

<http://patterns.projects.cis.ksu.edu/documentation/patterns/ctl.shtml>

Absence – P is false:	
Globally	$AG(!P)$
Before R	$A[(!P \mid AG(!R)) W R]$
After Q	$AG(Q \rightarrow AG(!P))$

Many of the mappings use the weak until operator (W) which is related to the strong until operator (U) by the following equivalences:

$$A[x W y] = !E[!y U (!x \& !y)]$$

$$E[x U y] = !A[!y W (!x \& !y)]$$

Pattern (Existence)

Existence P becomes true :	
Globally	$AF(P)$
(*) Before R	$A[!R \ W \ (P \ \& \ !R)]$
After Q	$A[!Q \ W \ (Q \ \& \ AF(P))]$
(*) Between Q and R	$AG(Q \ \& \ !R \ \rightarrow \ A[!R \ W \ (P \ \& \ !R)])$
(*) After Q until R	$AG(Q \ \& \ !R \ \rightarrow \ A[!R \ U \ (P \ \& \ !R)])$

Pattern (Universality)

Universality P is true :	
Globally	$AG(P)$
(*) Before R	$A[(P \mid AG(!R)) W R]$
After Q	$AG(Q \rightarrow AG(P))$
(*) Between Q and R	$AG(Q \ \& \ !R \rightarrow A[(P \mid AG(!R)) W R])$
(*) After Q until R	$AG(Q \ \& \ !R \rightarrow A[P W R])$

- It is possible to get to a state where **started** holds, but **ready** doesn't: $EF (\text{started} \wedge \neg \text{ready})$. To express impossibility, we simply negate the formula.
 - For any state, if a request (of some resource) occurs, then it will eventually be acknowledged: $AG (\text{requested} \rightarrow AF \text{ acknowledged})$.
 - A certain process is enabled infinitely often on every computation path: $AG (AF \text{ enabled})$.
 - From any state it is possible to get to a restart state: $AG (EF \text{ restart})$.
 - Altri esempi

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Important equivalences between CTL formulas

- We have already noticed that A is a universal quantifier on paths and E is the corresponding existential quantifier. Moreover, G and F are also universal and existential quantifiers, ranging over the states along a particular path.
- We can derive the following equivalences:
 - $\neg AF \varphi \equiv EG \neg\varphi$ and $EG \varphi \equiv \neg AF \neg\varphi$
 - $\neg EF \varphi \equiv AG \neg\varphi$ and $AG \varphi \equiv \neg EF \neg\varphi$
 - $\neg AX \varphi \equiv EX \neg\varphi$.
 - We also have the equivalences $AF \varphi \equiv A[\top U \varphi]$ and
 - $EF \varphi \equiv E[\top U \varphi]$ which are similar to the corresponding equivalences in LTL.
 - Adequate sets of CTL connectives: not all the connectives are necessary.
 - We could (and will) use only AF, EU, EX

- CTL allows explicit quantification over paths, and in this respect it is more expressive than LTL, as we have seen.
 - However, it does not allow one to select a range of paths by describing them with a formula, as LTL does. In that respect, LTL is more expressive. For example, in LTL we can say 'all paths which have a p along them also have a q along them,' by writing $F p \rightarrow F q$. It is not possible to write this in CTL because of the constraint that every F has an associated A or E.
 - CTL* is a logic which combines the expressive powers of LTL and CTL, by dropping the CTL constraint that every temporal operator (X, U, F, G) has to be associated with a unique path quantifier (A, E).
 - Past operators in LTL can be added.