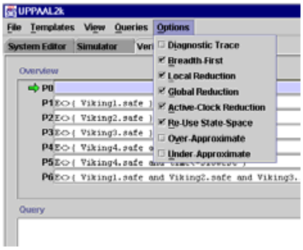
Inside the UPPAAL tool

- Data Structures
  - DBM's (Difference Bounds Matrices)
  - Canonical and Minimal Constraints
- Algorithms
  - Reachability analysis
  - Liveness checking
  - Termination
  - Verification Options

Verification Options


UPPAAL2k
File Templates View Queries Options
System Editor Simulator Veri
Overview
Query

□ Diagnostic Trace
☑ Breadth-First
☑ Local Reduction
☑ Global Reduction
☑ Active-Clock Reduction
☑ Re-Use State-Space
□ Over-Approximate
□ Under-Approximate

```
P0
P1 E<>( Viking1.safe )
P2 E<>( Viking2.safe )
P3 E<>( Viking3.safe )
P4 E<>( Viking4.safe a
P5 E<>( Viking4.safe and
P6 E<>( Viking1.safe and Viking2.safe and Viking3.
```

- Diagnostic Trace

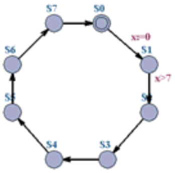
- Breadth-First
- Depth-First

- Local Reduction
- Active-Clock Reduction
- Global Reduction

- Re-Use State-Space

- Over-Approximation
- Under-Approximation

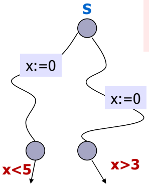
Inactive (passive) Clock Reduction



x is only *active* in location **S1**

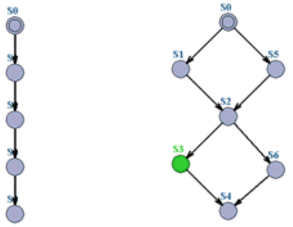
Definition

x is *inactive* at **S** if on all path from **S**, x is always reset before being tested.



Global Reduction

(When to store symbolic state)

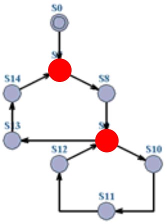


However, **Passed** list useful for efficiency

No Cycles: **Passed** list not needed for *termination*

Global Reduction [RTSS97]

(When to store symbolic state)



Cycles:
Only symbolic states involving loop-entry points need to be saved on **Passed** list

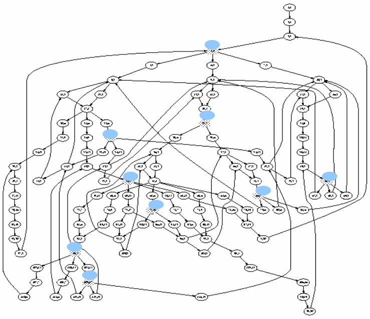
[RTSS97,CAV03]

To Store Or Not To Store?

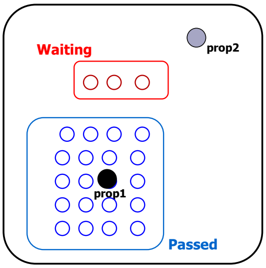
117 $\text{states}_{\text{total}}$
↓
81 $\text{states}_{\text{entrypoint}}$
↓
9 states

Time OH less than 10%

(need to re-explore some states)



Reuse of State Space



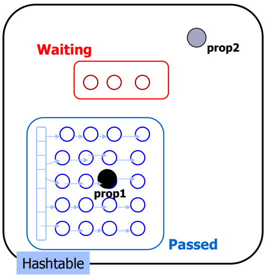
```
A[]  prop1

A[]  prop2
A[]  prop3
A[]  prop4
A[]  prop5
 .
 .
 .
A[]  propn
```

Search in existing **Passed** list before continuing search

Which order to search?

Reuse of State Space



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 .
 .
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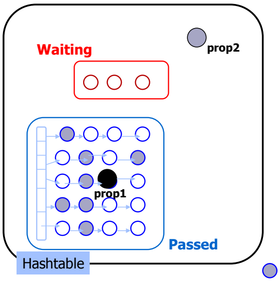
Which order to search?

Reuse of State Space



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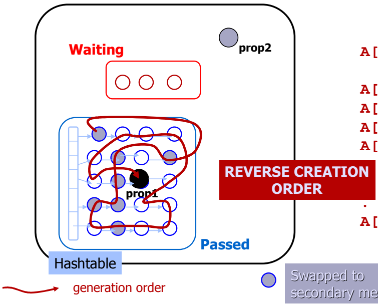
A[]  prop3
A[]  prop4
A[]  prop5
 .
 .
 .
A[]  propn
```

Search in existing **Passed** list before continuing search

Which order to search?

○ Swapped to secondary memory

Reuse of State Space



```
A[]  prop1

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A[]  prop3
A[]  prop4
A[]  prop5
 .
 .
 .
A[]  propn
```

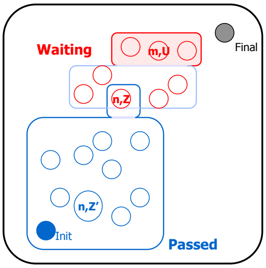
Search in existing **Passed** list before continuing search

Which order to search?

○ Swapped to secondary memory

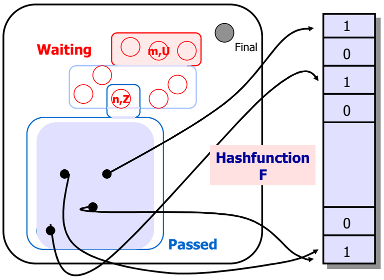
Under-approximation

Bitstate Hashing (Holzman,SPIN)



Under-approximation

Bitstate Hashing



Passed= Bitarray

UPPAAL 8 Mbits

Bit-state Hashing

```
INITIAL  Passed := Ø;
         Waiting := {(n0,Z0)}

REPEAT
  - pick  (n,Z) in Waiting
  - if for some Z′ ⊇ Z
     (n,Z′) in Passed then  STOP
  - else /explore/ add
           { (m,U) : (n,Z) => (m,U) }
           to Waiting;
           Add  (n,Z)  to Passed

UNTIL  Waiting = Ø
           or
           Final is in Waiting
```

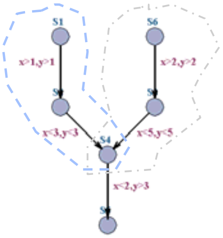
Passed(**F**(n,Z)) = **1**

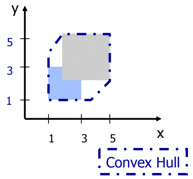
Passed(**F**(n,Z)) := **1**

Under Approximation
(good for finding Bugs quickly, debugging)

- Possitive answer is safe (you can trust)
  - You can trust your tool if it tells:
    - a state is reachable (it means Reachable!)
- Negative answer is Inconclusive
  - You should not trust your tool if it tells:
    - a state is non-reachable
  - Some of the branch may be terminated by conflict (the same hashing value of two states)

Over-approximation
Convex Hull





Over-Approximation
(good for safety property-checking)

- Possitive answer is Inconclusive
  - a state is reachable means Nothing
    (you should not trust your tool when it says so)
  - Some of the transitions may be enabled by Enlarged zones
- Negative answer is safe
  - a state is not reachable means Non-reachable
    (you can trust your tool when it says so)

OUTLINE

- A Brief Introduction
  - Motivation ... what are the problems to solve
  - CTL, LTL and basic model-checking algorithms
- Timed Systems
  - Timed automata and verification problems
  - UPPAAL tutorial (1): data stuctures & algorithms
  - ➡ UPPAAL tutorial (2): input languages
  - TIMES: From models to code ”guaranteeing” timing constraints
- Further topics/Recent Work
  - Systems with buffers/queues [CAV 2006]

Lecture 7

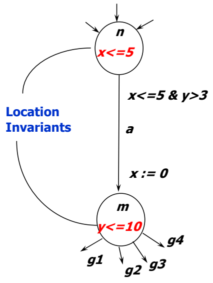
UPPAAL tutorial (2)

The UPPAAL input languages:
timed automata & TCTL in UPPAAL

[Henzinger,Sifakis et al, 1992]

Timed Automata

+ Invariants



Location Invariants

Clocks: *x, y*

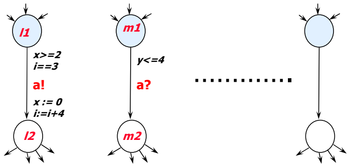
Transitions:

$(\boldsymbol{n}, \boldsymbol{x}=2.4, \boldsymbol{y}=3.1415) \cancel{\xrightarrow{e(3.2)}}$

$(\boldsymbol{n}, \boldsymbol{x}=2.4, \boldsymbol{y}=3.1415) \xrightarrow{e(1.1)} (\boldsymbol{n}, \boldsymbol{x}=3.5, \boldsymbol{y}=4.2415)$

Location invariants are used to force an automata to progress (i.e. leave the location) before the invariant becomes false.

Networks of Timed Automata



Two-way synchronization on **complementary** actions.

Closed Systems!

UPPAAL modeling language

- Networks of Timed Automata with Invariants
  + urgent action channels,
  + broadcast channels,
  + urgent and committed locations,
  + data-variables (with bounded domains),
  + arrays of data-variables,
  + constants,
  + guards and assignments over data-variables and arrays…,
  + templates with local clocks, data-variables, and constants
  + C subset

Declarations in UPPAAL

- The syntax used for declarations in UPPAAL is similar to the syntax used in the C programming language.
- **Clocks**:
  - **Syntax:**

```
clock x1, …, xn ;
```

  - **Example:**
  - `clock x, y;` **Declares two clocks: x and y.**

Declarations in UPPAAL (cont.)

- **Data variables**
  - **Syntax:**

```
int n1, … ;
int[l,u] n1, … ;
int n1[m], … ;
```

Integer with "default" domain.
Integer with domain from "l" to "u".
Integer array w. elements n1[0] to n1[m-1].

  - **Example;**
  - `int a, b;`
  - `int[0,1] a, b[5];`

Declarations in UPPAAL (cont.)

- Actions (or channels):
  - **Syntax:**

```
chan a, … ;
urgent chan b, … ;
```

Ordinary channels.
Urgent actions (described later)

  - **Example:**
  - `chan a, b[2];`
  - `urgent chan c;`

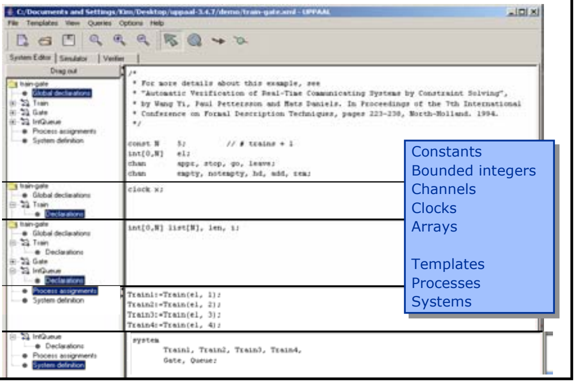
Declarations UPPAAL (const.)

- Constants
  - **Syntax:**

```
const int c1 = n1;
```

  - **Example:**
  - `const int[0,1] YES = 1;`
  - `const bool NO = false;`

Declarations in UPPAAL


C:/Documents and Settings/Kim/Desktop/uppaal-3.4.7/demo/train-gate.xml - UPPAAL
File Templates View Queries Options Help
System Editor | Simulator | Verifier
Drag out
train-gate
Global declarations
Train
Gate
IntQueue
Process assignments
System definition
Declarations

```
/*
 * For more details about this example, see
 * "Automatic Verification of Real-Time Communicating Systems by Constraint Solving",
 * by Wang Yi, Paul Pettersson and Mats Daniels. In Proceedings of the 7th International
 * Conference on Formal Description Techniques, pages 223-238, North-Holland. 1994.
 */

const N     5;          // # trains + 1
int[0,N]    el;
chan        appr, stop, go, leave;
chan        empty, notempty, hd, add, rem;
```

```
clock x;
```

```
int[0,N] list[N], len, i;
```

```
Train1:=Train(el, 1);
Train2:=Train(el, 2);
Train3:=Train(el, 3);
Train4:=Train(el, 4);
```

```
system
      Train1, Train2, Train3, Train4,
      Gate, Queue;
```

Constants
Bounded integers
Channels
Clocks
Arrays

Templates
Processes
Systems

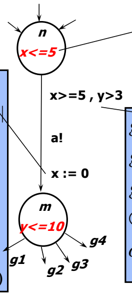
Timed Automata in UPPAAL

Clock Assignments

$x := n$

Variable Assignments

$i := Expr$
$Expr ::= i \mid i[Expr] \mid$
$n \mid -Expr \mid$
$Expr + Expr \mid$
$Expr - Expr \mid$
$Expr * Expr \mid$
$Expr / Expr \mid$
$(g_d\,?\,Expr : Expr)$



Location Invariants

$inv ::= x < n \mid x <= n \mid inv, inv$

clock **natural number** **"and"**

$g ::= g_c \mid g_d \mid g, g$
$g_c ::= x \otimes n \mid x \otimes y + n$
$g_d ::= Expr\ op\ Expr$
$\otimes \in \{<, <=, ==, >=, >\}$
$op \in \{<, <=, ==, >=, >, !=\}$

Clock guards

Data guards

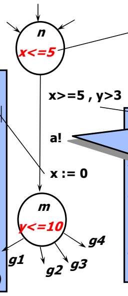
Timed Automata in UPPAAL

Clock Assignments

$x := n$

Variable Assignments

$i := Expr$
$Expr ::= i \mid i[Expr] \mid$
$n \mid -Expr \mid$
$Expr + Expr \mid$
$Expr - Expr \mid$
$Expr * Expr \mid$
$Expr / Expr \mid$
$(g_d\,?\,Expr : Expr)$



Location Invariants

$inv ::= x < n \mid x <= n \mid inv, inv$

clock **natural number** **"and"**

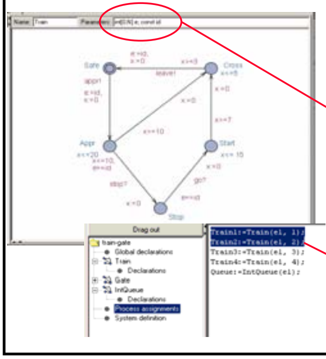
Actions:

- **"a" name of action**
- **a! or a?**
- **one or zero per edge**

guards

guards

Templates in UPPAAL



```
Train1:=Train(el, 1);
Train2:=Train(el, 2);
Train3:=Train(el, 3);
Train4:=Train(el, 4);
Queue:=IntQueue(el);
```

- Templates may be parameterised:

```
int v; const min; const max

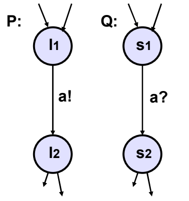
int[0,N] e; const id
```

- Templates are instantiated to form processes:

```
P:= A(i,1,5);
Q:= A(j,0,4);

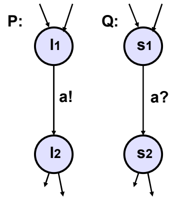
Train1:=Train(el, 1);
Train2:=Train(el, 2);
```

Urgent Channels: Example 1



- Suppose the two edges in automata P and Q should be taken as soon as possible.
- I.e. as soon as both automata are ready (simultaneously in locations l_1 and s_1).
- How to model with invariants if either one may reach l_1 or s_1 first?

Urgent Channels: Example 1



- Suppose the two edges in automata P and Q should be taken as soon as possible
- I.e. as soon as both automata are ready (simultaneously in locations l_1 and s_1).
- How to model with invariants if either one may reach l_1 or s_1 first?
- **Solution**: declare action "a" as urgent.

Urgent Channels

```
urgent chan hurry;
```

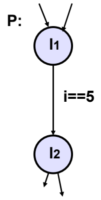
Informal Semantics:

- There will be no delay if transition with urgent action can be taken.

Restrictions:

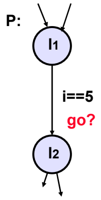
- No clock guard allowed on transitions with urgent actions.
- Invariants and data-variable guards are allowed.

Urgent Channel: Example 2

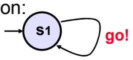


- Assume i is a data variable.
- We want P to take the transition from l1 to l2 as soon as i==5.

Urgent Channel: Example 2



- Assume i is a data variable.
- We want P to take the transition from l1 to l2 as soon as i==5.
- **Solution**: P can be forced to take transition if we add another automaton:



where "go" is an urgent channel, and we add "go?" to transition l1→l2 in automaton P.

Broadcast Synchronisation

```
broadcast chan a, b, c[2];
```

- If a is a broadcast channel:
  `a!` = Emmision of broadcast
  `a?` = Reception of broadcast
- A set of edges in different processes can synchronize if one is emitting and the others are receiving on the same b.c. channel.
- A process can always emit.
- Receivers *must* synchronize if they can.
- No blocking.

Urgent Location

Click "Urgent" in State Editor.

Informal Semantics:

- No delay in urgent location.

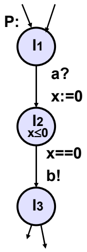
Note: the use of urgent locations **reduces** the number of clocks in a model, and thus the complexity of the analysis.

Urgent Location: Example

- Assume that we model a simple media M:

that receives packages on channel a and immediately sends them on channel b.

- P models the media using clock x.

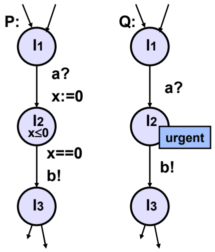


Urgent Location: Example

- Assume that we model a simple media M:

that receives packages on channel a and immediately sends them on channel b.

- P models the media using clock x.
- Q models the media using **urgent location**.
- P and Q have the same behavior.



Committed Location

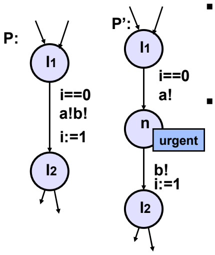
Click “Committed” i State Editor.

Informal Semantics:

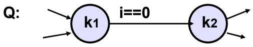
- No delay in committed location.
- Next transition must involve automata in committed location.

Note: the use of committed locations **reduces** the number of interleaving in state space exploration (and also the number of clocks in a model), and thus allows for more space and time efficient analysis.

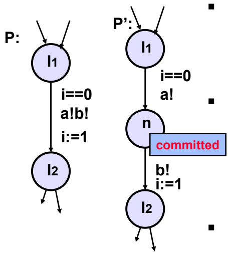
Committed Location: Example 1



- **Assume:** we want to model a process (P) simultaneously sending message a and b to two receiving processes (when i==0).
- P' sends “a” two times at the same time instant, but in location “n” other automata, e.g. Q may interfear



Committed Location: Example 1



- **Assume:** we want to model a process (P) simultaneously sending message (a) to two receiving processes (when i==0).
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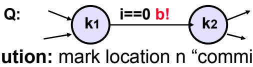
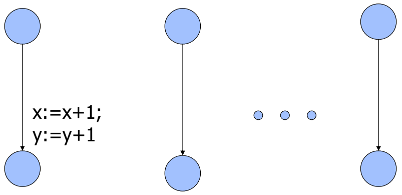


- **Solution:** mark location n “committed” in automata P' (instead of “urgent”).

Committed Locations

(example: atomic sequence in a network)

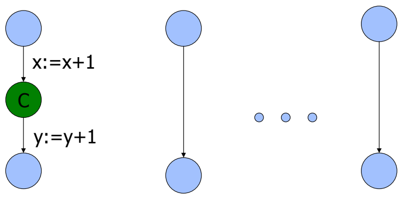


If the sequence becomes too long, you can split it ...

Committed Locations

(example: atomic sequence in a network)

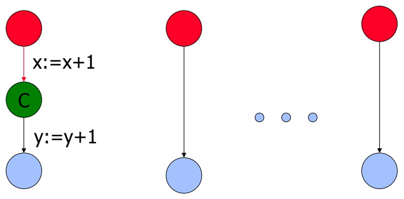
Semantics: the time spent on C-location should be zero !



Committed Locations

(example: atomic sequence in a network)

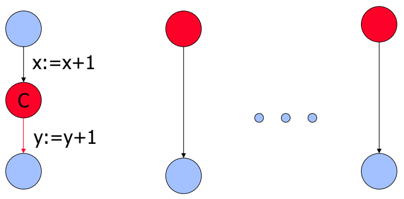
Semantics: the time spent on C-location should be zero !



Committed Locations

(example: atomic sequence in a network)

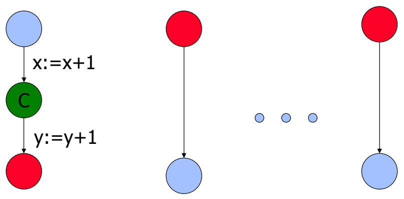
Semantics: the time spent on C-location should be zero !



Now, only the committed (red) transition can be taken!

Committed Locations

(example: atomic sequence in a network)

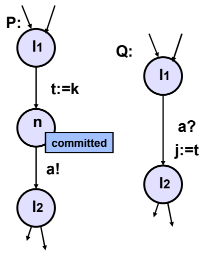


Committed Locations

- A trick of modeling (e.g. to model multi-way synchronization using handshaking)
- More importantly, it is a simple and efficient mechanism for state-space reduction!
  In fact, it is a simple form of 'partial order reduction'
- It is used to avoid intermediate states, interleavings:
  Committed states are not stored in the passed list
  Interleavings of any state with a committed location will not be explored

Committed Location: Example 2

- **Assume:** we want to pass the value of integer "k" from automaton P to variable "j" in Q.
- The value of k can is passed using a global integer variable "t".
- Location "n" is committed to ensure that no other automat can assign "t" before the assignment "j:=t".



More Expressions

- New operators (not clocks):
  - Logical:
    - && (logical and), || (logical or), ! (logical negation),
  - Bitwise:
    - ^ (xor), & (bitwise and), | (bitwise or),
  - Bit shift:
    - << (left), >> (right)
  - Numerical:
    - % (modulo), <? (min), >? (max)
  - Compound Assignments:
    - +=, -=, *=, /=, ^=, <<=, >>=
  - Prefix or Postfix:
    - ++ (increment), -- (decrement)

More on Types

- Multi dimensional arrays

  e.g. int b[2][3];
- Array initialiser:

  e.g. int b[2][3] := { {1,2,3}, {4,5,6} };
- Arrays of channels, clocks, constants.

  e.g.
  - chan a[3];
  - clock c[3];
  - const k[3] { 1, 2, 3 };
- Broadcast channels.

  e.g. broadcast chan a;

Extensions

Select statement

- Models non-deterministic choise
- `x : int[0,42]`

Types

- Record types
- Type declarations
- Meta variables:

  not stored with state

  `meta int x;`

Forall / Exists Expressions

- `forall (x:int[0,42]) expr`

  true if expr is true for *all* values in [0,42] of x
- `exists (x:int[0,4]) expr`

  true if expr is true for *some* values in [0,42] of x

Example:

```
forall
(x:int[0,4])array[x];
```

Advanced Features

- Priorities on channels

```
chan a,b,c,d[2],e[2];
chan priority a,d[0] < default < b,e
```

- Priorities on processes

```
system A < B,C < D;
```

- Functions

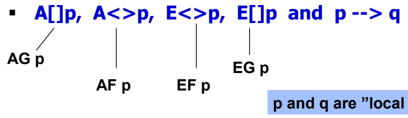
  C-like functions with return values

UPPAAL specification language

TCTL Quantifiers in UPPAAL

- E - exists a path (“**E**” in UPPAAL).
- A - for all paths (“**A**” in UPPAAL).
- G - all states in a path (“**[]**” in UPPAAL).
- F - some state in a path (“**<>**” in UPPAAL).

You may write the following queries in UPPAAL:



- **A[]p, A<>p, E<>p, E[]p and p --> q**

p and q are ”local properties”

"Local Properties"

`A[]p, A<>p, E<>p, E[]p, p-->p`
where `p` is a local property

automaton location

data guard

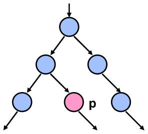
clock guard

p::= a.l | g_d | g_c | p and p |
p or p | not p | p imply p |
(p)

process/ name

E<>p – "p Reachable"

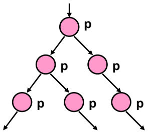
- **`E<>` p** – it is possible to reach a state in which p is satisfied.



- p is true in (at least) one reachable state.

A[]p – "Invariantly p"

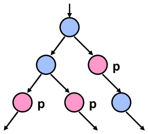
- **`A[]` p** – p holds invariantly.



- p is true in all reachable states.

A<>p – "Inevitable p"

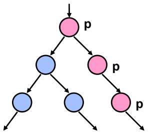
- **`A<>` p** – p will inevitable become true, the automaton is guaranteed to eventually reach a state in which p is true.



- p is true in some state of all paths.

E[ ] p – "Potentially Always p"

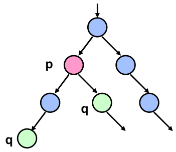
- **`E[]` p** – p is potentially always true.



- There exists a path in which p is true in all states.

p --> q– "p lead to q"

- **p** --> **q** – if p becomes true, q will inevitably become true.
  same as A[](**p** imply A<> **q**)



- In all paths, if p becomes true, q will inevitably become true.