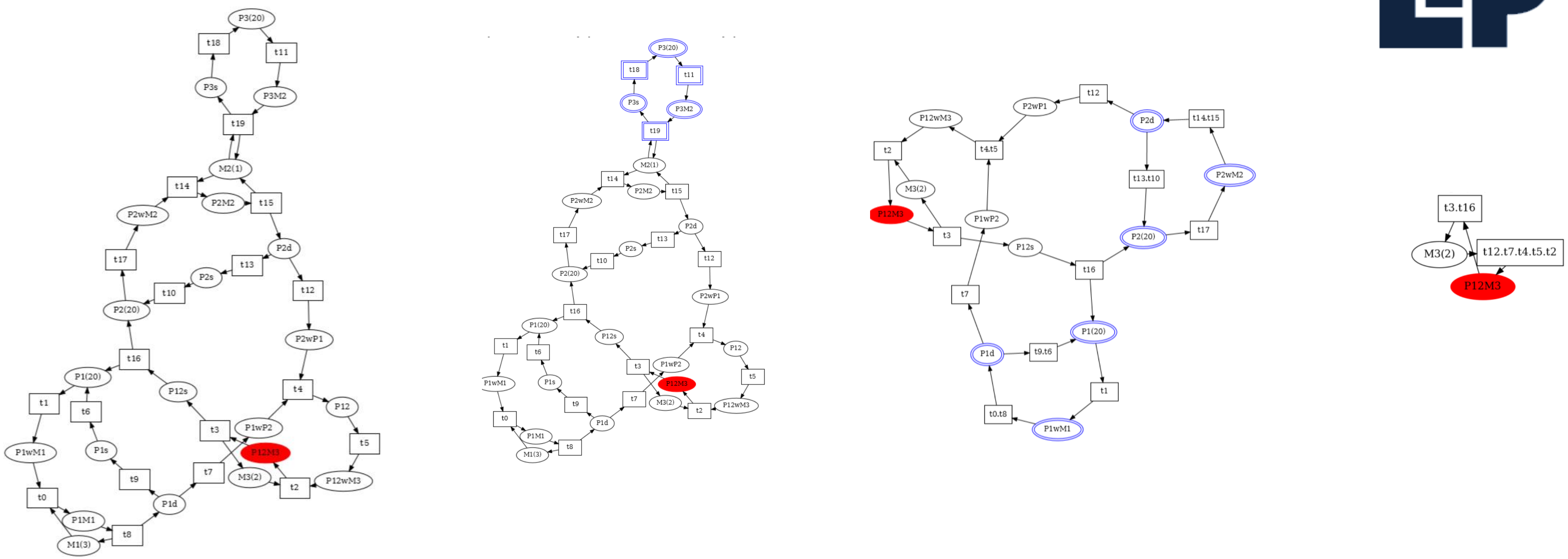

STRUCTURAL REDUCTIONS REVISITED

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LIP6, Sorbonne Université, CNRS

Petri Nets 2020, June 2020, Paris

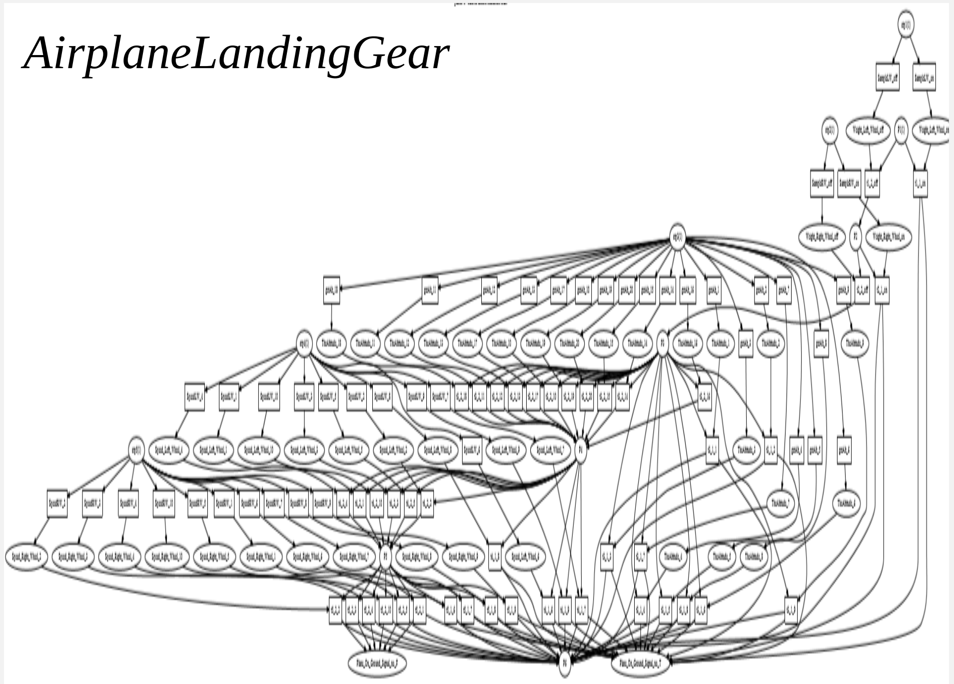
41ST INTERNATIONAL CONFERENCE ON APPLICATION AND THEORY OF PETRI NETS AND CONCURRENCY

VERIFYING PROPERTIES OF PETRI NETS

Properties of interest

Deadlock Detection

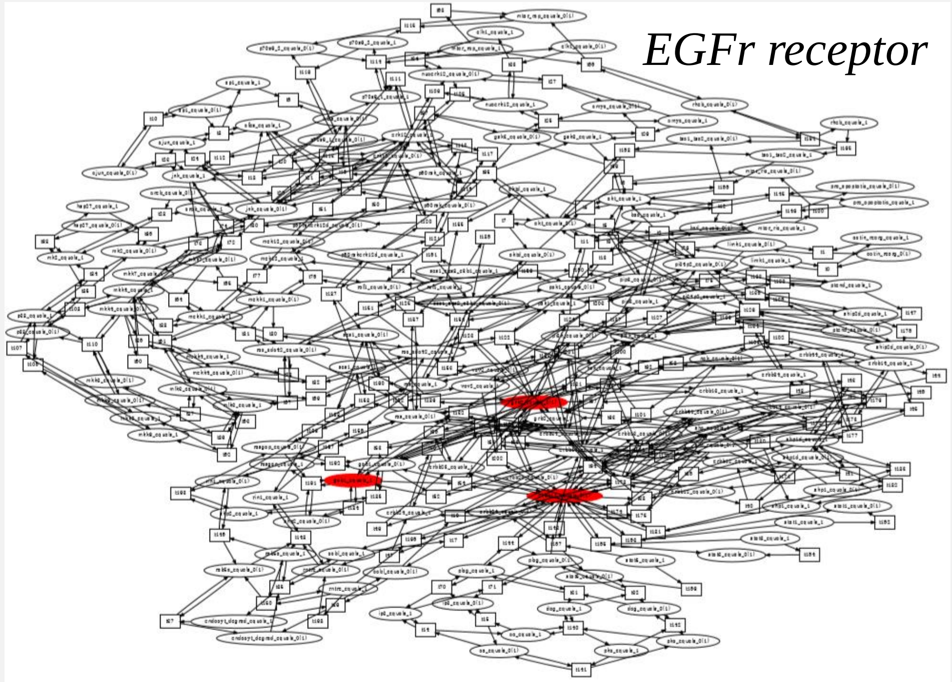
AirplaneLandingGear



Can a deadlock state be reached ?

Safety Properties

EGFr receptor

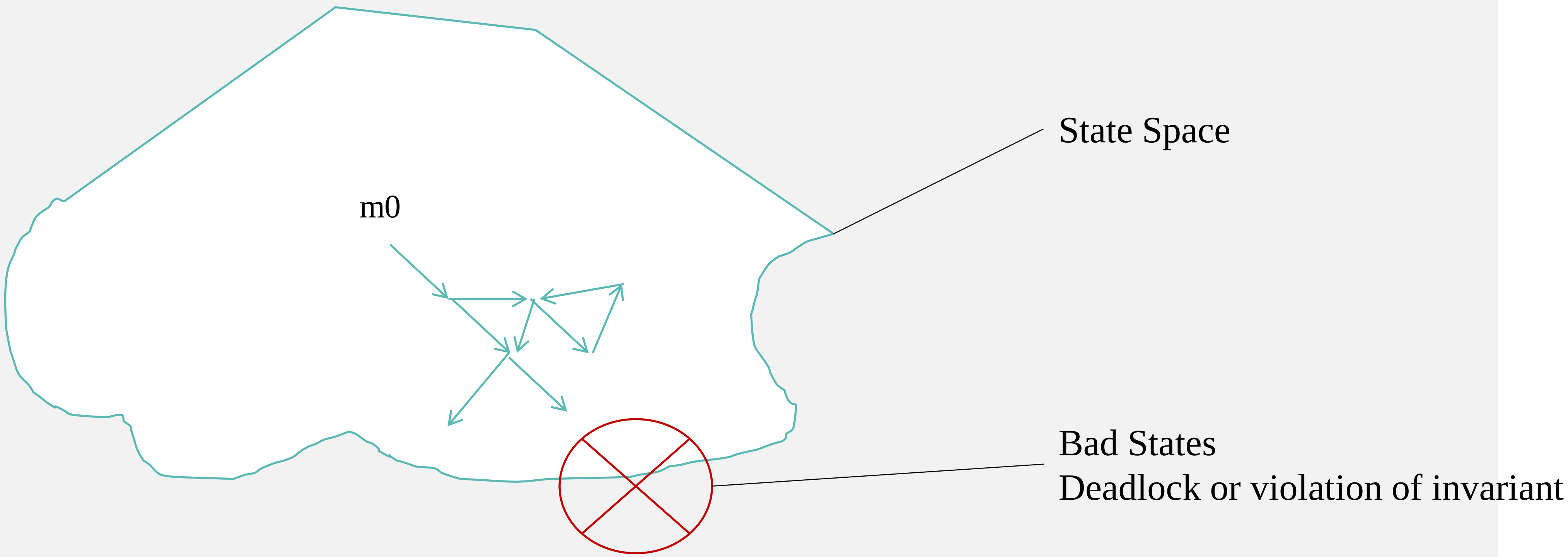


Is « m(P1) < m(P2) OR m(p3) <= 2 » an invariant ?

EXPLORING THE STATE SPACE

Petri net vs. State space (marking graph)

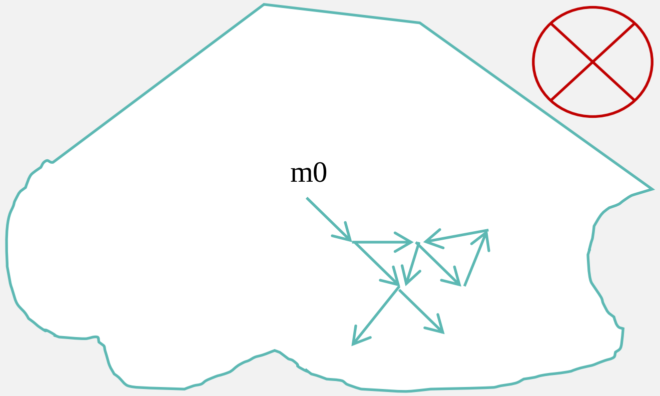
- Do reachable and « bad » states intersect ?



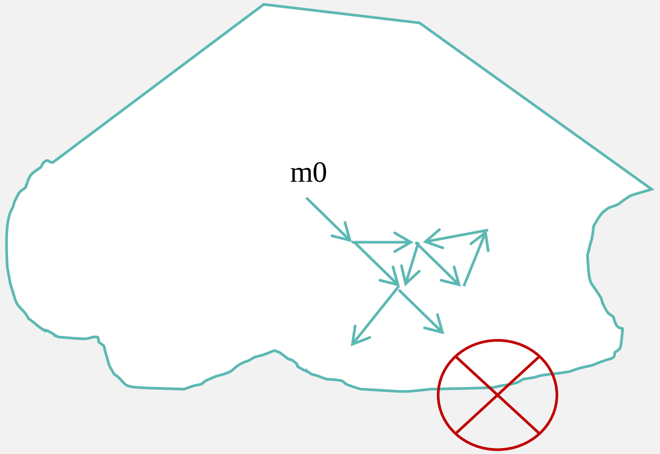
VERIFICATION OF AN INVARIANT

Petri net vs. State space (marking graph)

- Does my invariant hold in all reachable states of the net ?



Empty intersection
We **cannot** reach a bad state
Invariant is TRUE



Non-empty intersection
We can reach a bad state
Invariant is FALSE

OUR APPROACH

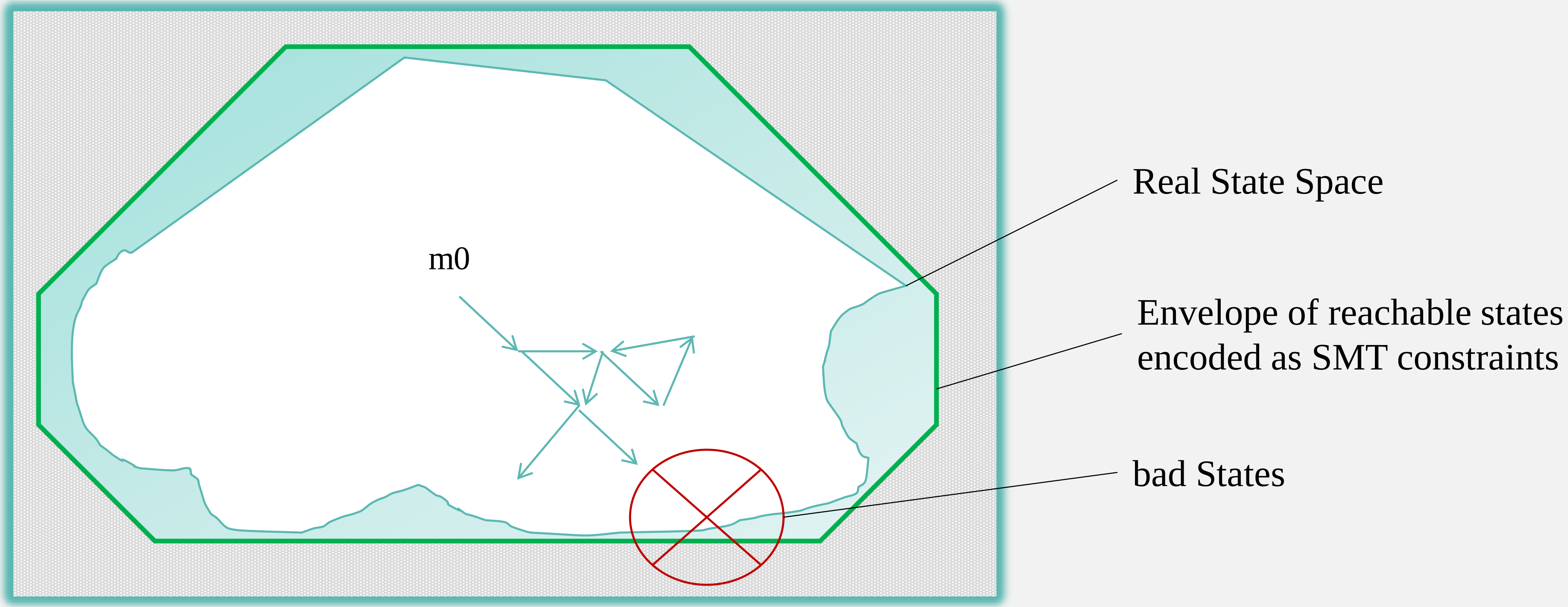
Three complementary strategies

1. Over-approximation
    - Can formally *prove* **TRUE** invariants
    - SMT based constraints to approximate reachable states
2. Under-approximation
    - Can *contradict* **FALSE** invariants if it can produce a counter-example
    - Sampling using a pseudo-random walk
3. Property preserving reduction
    - Produce a smaller net that preserves existence of reachable bad states
    - Property specific structural reduction rules

1. OVER-APPROXIMATE WITH SMT

Leveraging SAT Modulo Theory SMT

- Describe constraints on reachable states : an envelope

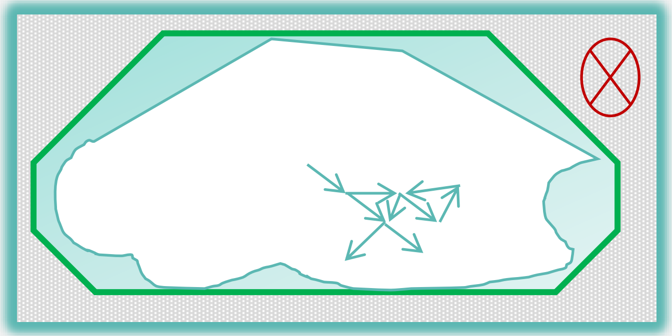


- The envelope is a much simpler object than the actual state space.

1. OVER-APPROXIMATE WITH SMT

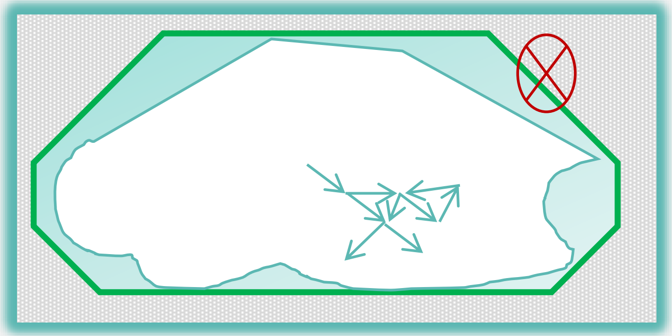
Can we find an bad state in the envelope ?

NO INTERSECTION (UNSAT)



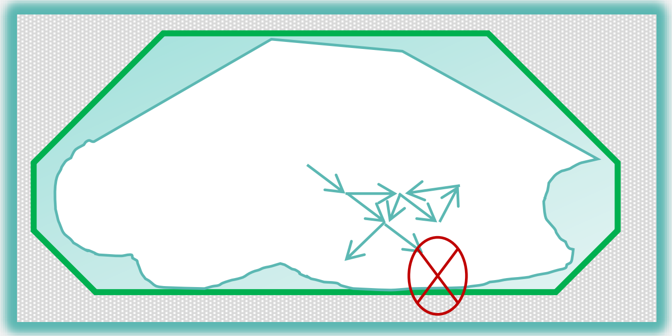
Over-approximation => Invariant holds.

WITH INTERSECTION (SAT)



False Positive

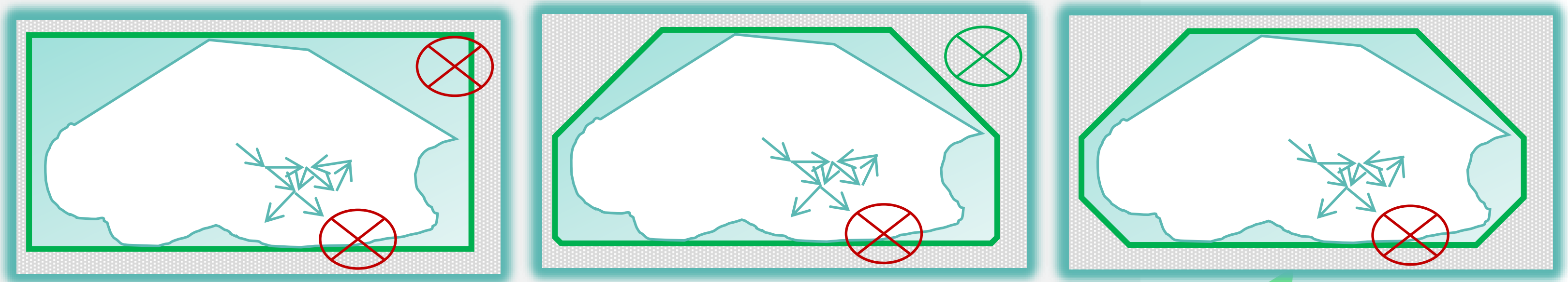
OR



Over-approximation => **INCONCLUSIVE**
but we can provide a candidate solution (SAT model).

SMT CONSTRAINTS

Highlights



Iterative refinement of the over approximation

- Places = variables
  - P1 >= 0, P2 >= 0…
- Generalized flows
  - P1 + 2*P2 – P3 = 1
- Trap constraints
  - P1 > 0 OR P2 > 0
  - Compute ***useful constraints*** as separate SMT problem
- State Equation
  - Add a positive variable for firing count of transitions
  - P1 = T1 – T2 + 1
- Read => Feed
  - T1 reads P; m0(P)=0 ; T2 and T3 feed P
  - T1 > 0 => T2 > 0 OR T3 > 0
- Causal constraints (*precedes* is a strict partial order)
  - T1 consumes from P ; m0(P)=0 ; T2 and T3 feed P
  - T1 > 0 => (T2>0 AND T2 *precedes* T1) OR (T3 >0 AND T3 *precedes* T1)
  - Is inconsistent (UNSAT) if we also have « T1 *precedes* T2 » and « T1 *precedes* T3 »

+Incremental constraints
+Use Reals then Integers
+UNSAT = invariant proved true
+SAT = candidate state + firing count

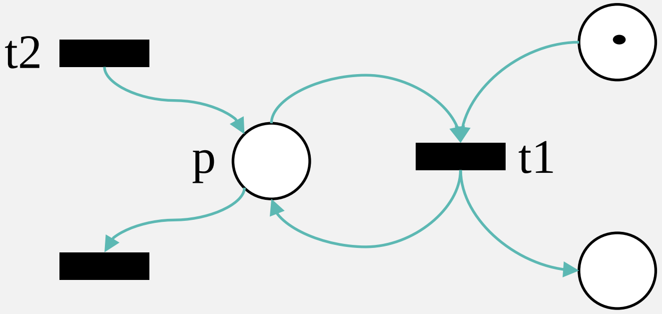
TRAP CONSTRAINTS

An initially marked trap cannot be emptied

- A trap is a set of places of the net
  - Any transition ***consuming*** from the trap must also ***feed*** the trap
- As noted by Esparza et al. in 2000, good complement to state equation
  - Complex mutex protocols e.g. Peterson, Lamport
  - But worst case exponential number of traps
- Iterative process :
  - When main SMT procedure is SAT : examine candidate solution
  - We use a separate SMT solver to find relevant traps :
    - Can we find an initially marked trap that is unmarked in the candidate ?
      - SAT => add the trap constraint to main engine and try again
      - UNSAT => no trap constraints that contradict the candidate exist

READ => FEED

Constraining the transition firing count



- The state equation ignores read arcs

  ⇒ spurious solutions, **t1** and **t2** *are not correlated* in the state equation constraints

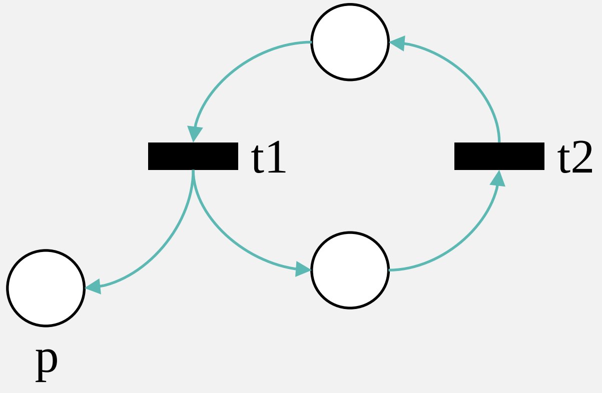
Reason on first occurrence of each transition :

- If a transition has positive firing count and reads in place « p » initially empty, it must be the case that a transition feeding « p » also has positive firing count.

  $t1 > 0 \Rightarrow t2 > 0$

CAUSAL CONSTRAINTS (UNSAT)

A partial order on first occurrence of each transition



The state equation can borrow non existing tokens

$\Rightarrow$ t1=1 and t2=1 is a solution to the state equation to mark « p »

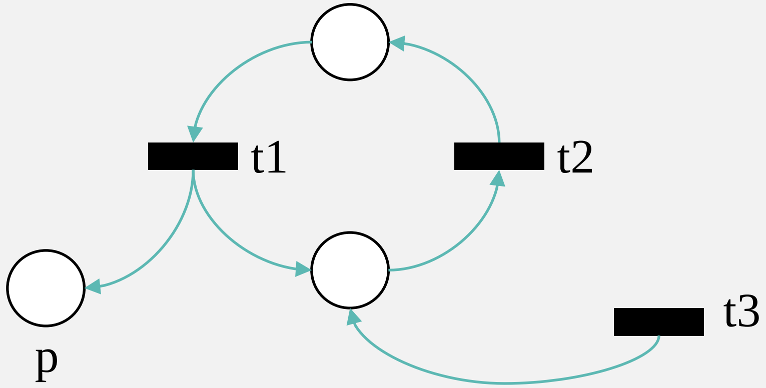
We assert that :

- t1 > 0 => t2 > 0 and t2 precedes t1
- t2 > 0 => t1 > 0 and t1 precedes t2

Obtaining a contradiction (UNSAT) as soon as t1 or t2 positive in the solution

CAUSAL CONSTRAINTS (SAT)

A partial order on first occurrence of each transition



The state equation can borrow non existing tokens

⇒ t1=1 and t2=1 is a solution to the state equation to mark « p »

We assert that :

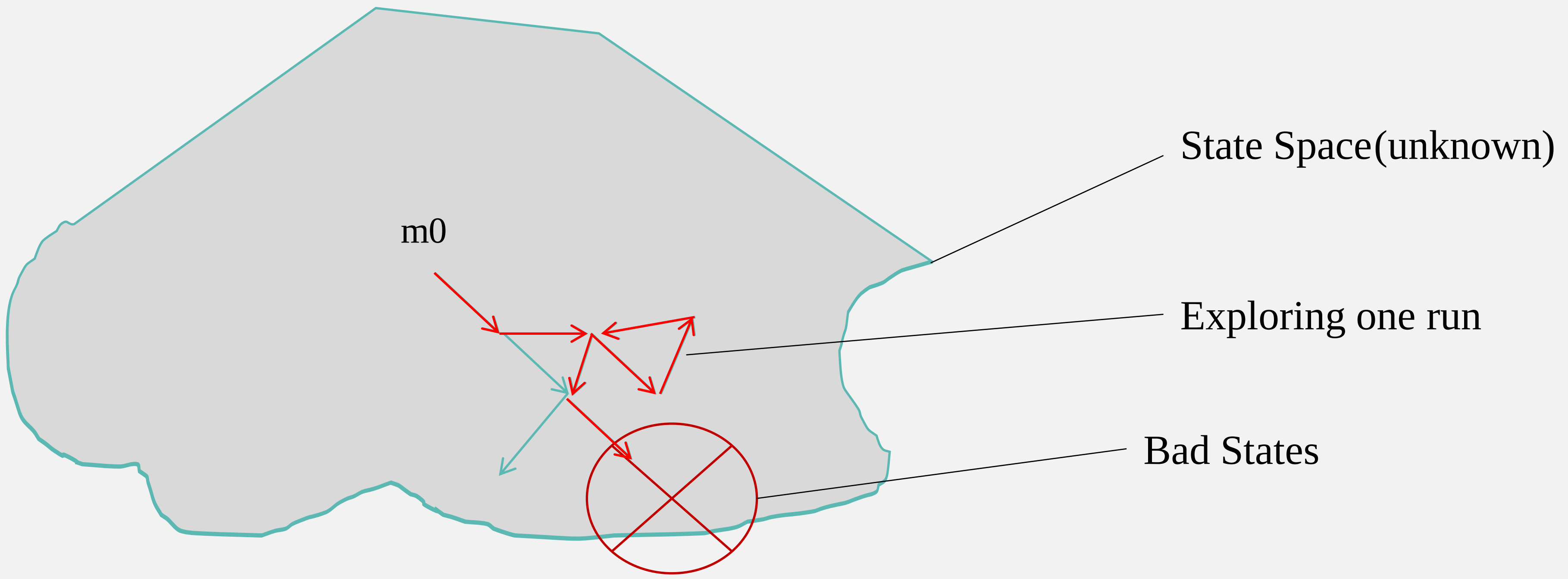
- t1 > 0 => t2 > 0 and t2 precedes t1
- t2 > 0 => (t1 > 0 and t1 precedes t2) OR (t3 > 0 and t3 precedes t2)

Obtaining a solution (SAT) : t3 precedes t2 precedes t1

2. UNDER-APPROXIMATE WITH SAMPLING

Memory-less random exploration of the state space

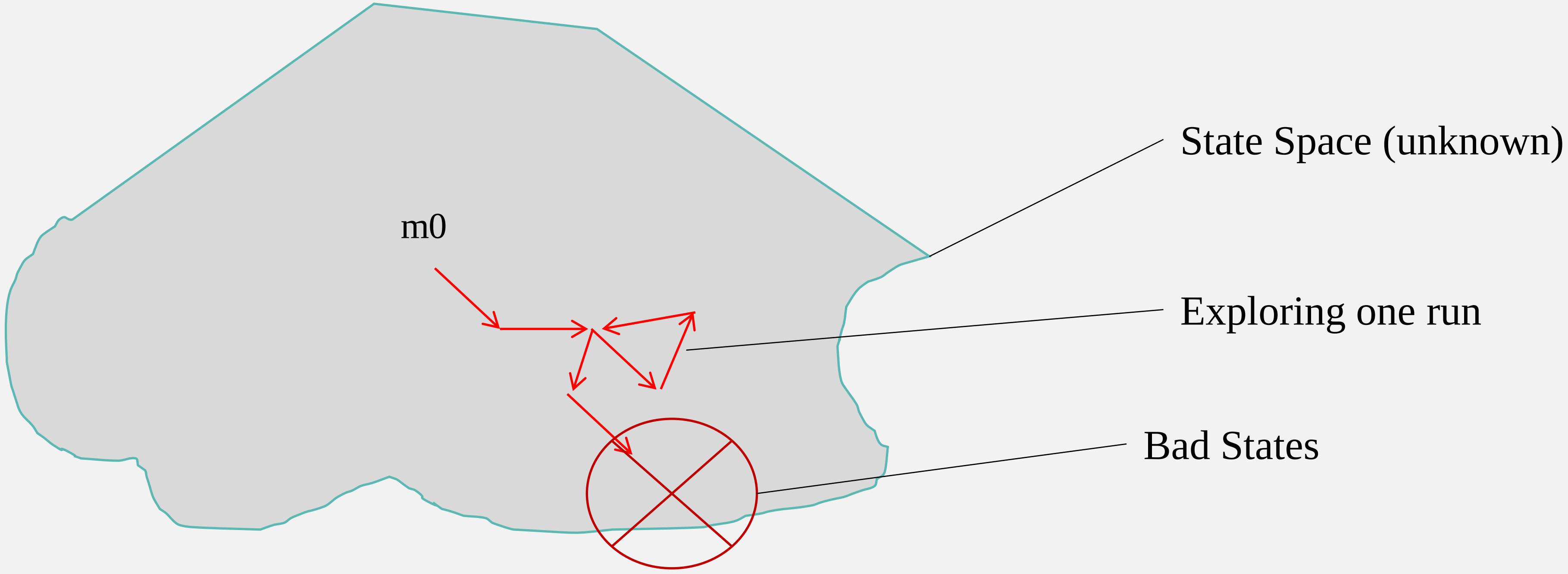
- Execute the net, trying to find a reachable bad state



2. UNDER-APPROXIMATE WITH SAMPLING

Memory-less pseudo-random walk of the state space

- Execute the net, trying to find a reachable bad state (counter-example)



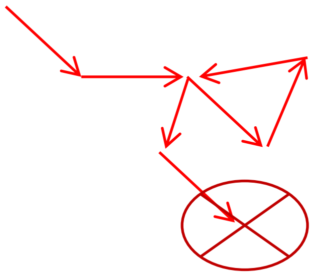
If an bad state is met => Invariant **DOES NOT** hold.
Otherwise **INCONCLUSIVE :**

- we might have been unlucky and not found the bug,
- or the bug might genuinely not exist.

RANDOM WALKS

Highlights

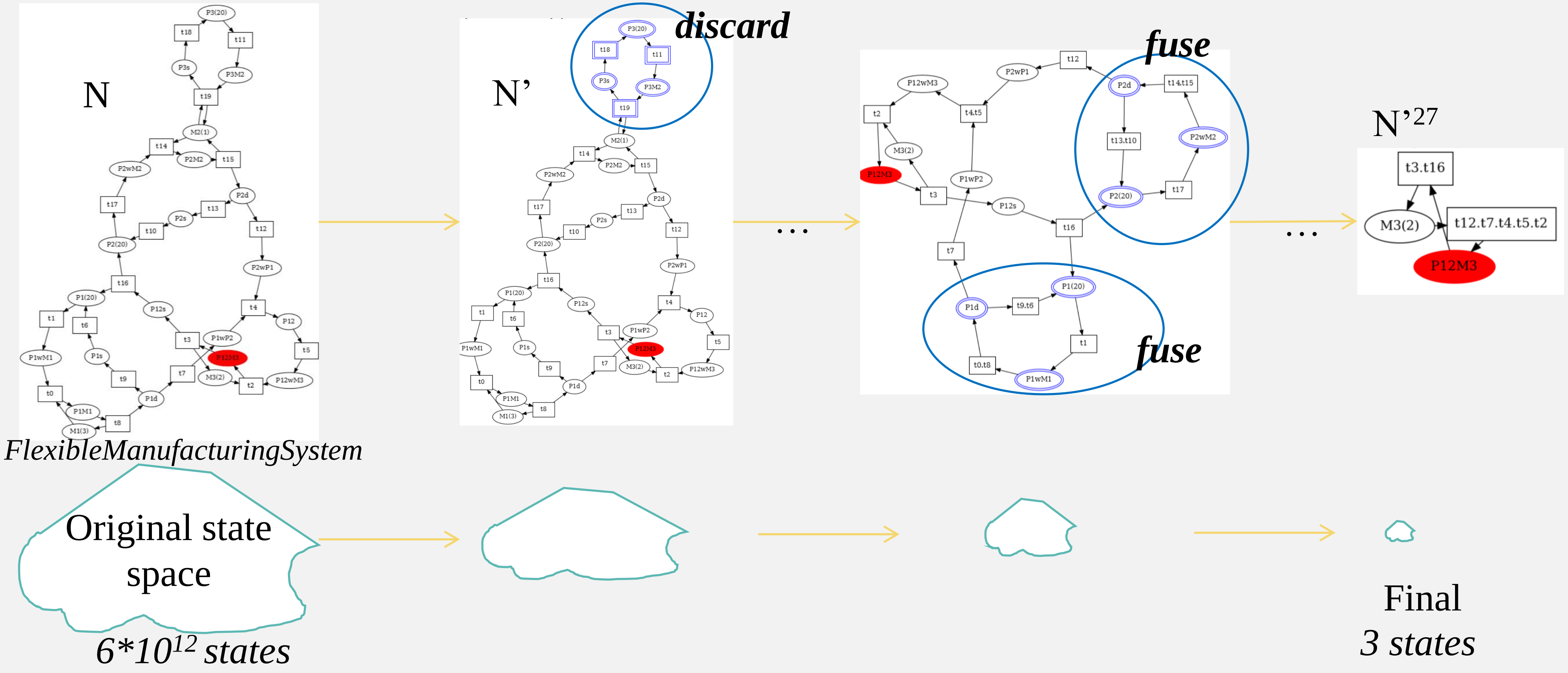
- Fast sparse implementation
  - Avoid TxT or PxP matrices
- Some states exponentially unlikely to be met by pure random walk
  - Use multiple heuristics each with a strong bias
- Guiding the walk :
  - Pure random walk with resets
  - **Guided by a firing count coming from an SMT « SAT » result**
  - Guided by the property (choose « best » successor w/ heuristic)
  - Recently enabled / Not recently used
  - …
- Random walk is fast and scales well
  - Always first try to disprove with random walk **before** trying to prove with SMT.



+Fast results in many FALSE cases
+Disprove by counter-example
+Complements SMT TRUE proofs
+Guided by SMT inconclusive SAT

3. PROPERTY SPECIFIC STRUCTURAL REDUCTIONS

*Incrementally build a smaller net using **structural reduction rules***



Each transformation **rule** produces a net N' that satisfies the property **if and only if** original net N satisfies it.

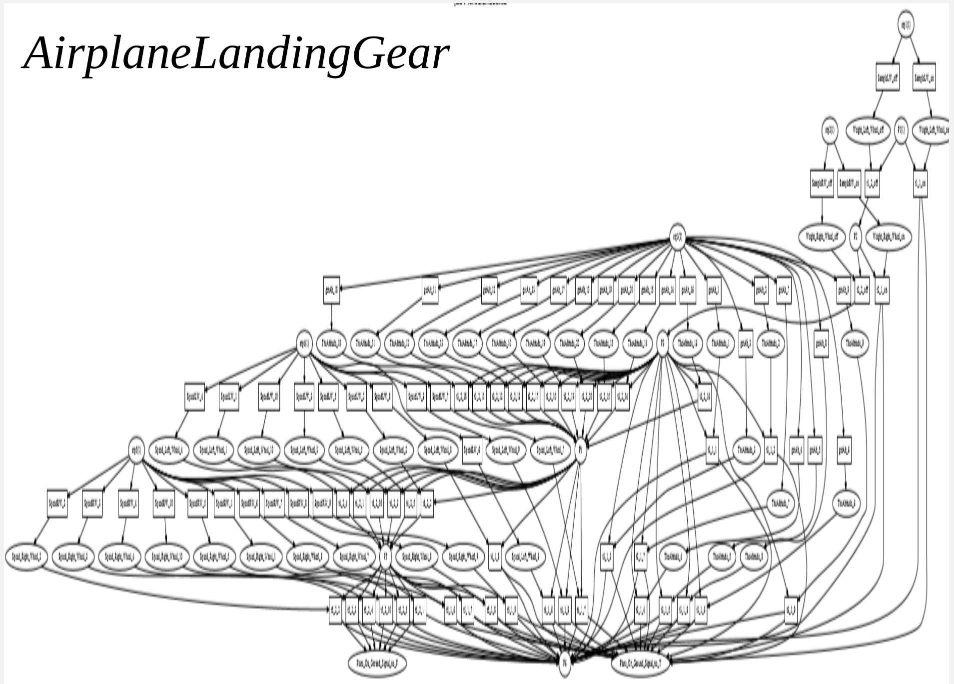
Reduction of the Petri net structure typically induces an **exponential** state space reduction.

PROPERTY SPECIFIC ?

Properties of interest

Deadlock Detection

AirplaneLandingGear



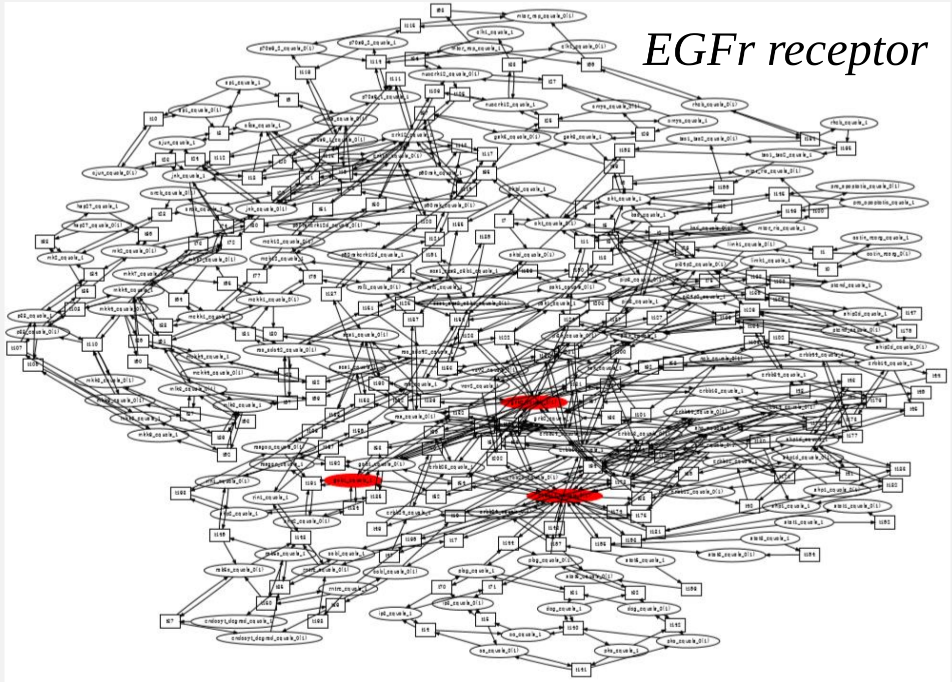
Can a deadlock state be reached ?

=> Existence of **at least one** finite trace.

Specific rules preserving only unavoidable loops.

Safety Properties

EGFr receptor

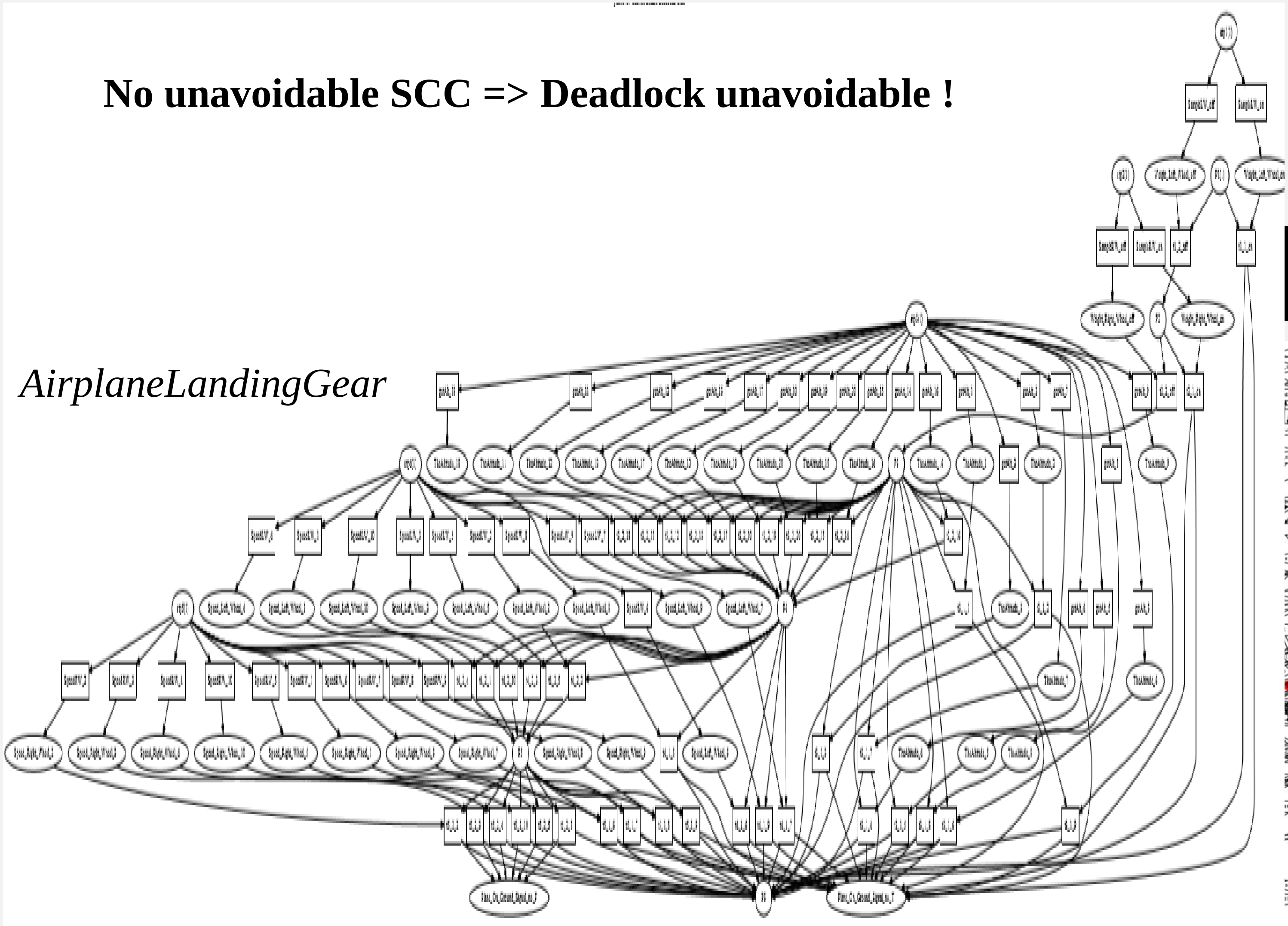


Is « m(P1) < m(P2) OR m(p3) <= 2 » an invariant ?

Focus on a **projection** of reachable states over the places in the *support.*

No unavoidable SCC => Deadlock unavoidable !

AirplaneLandingGear



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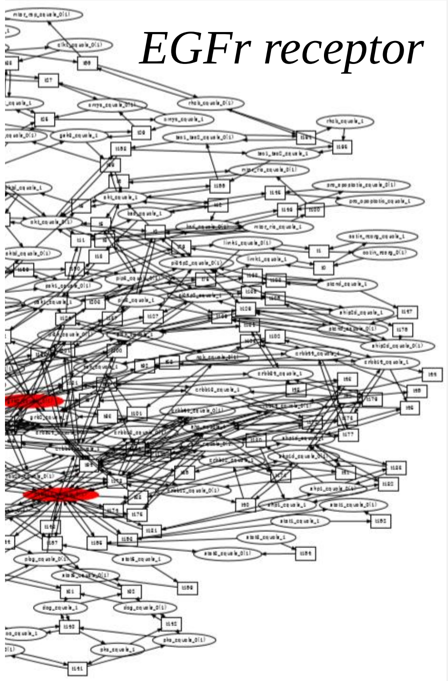

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PROPERTY SPECIFIC ?

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Deadlock Detection

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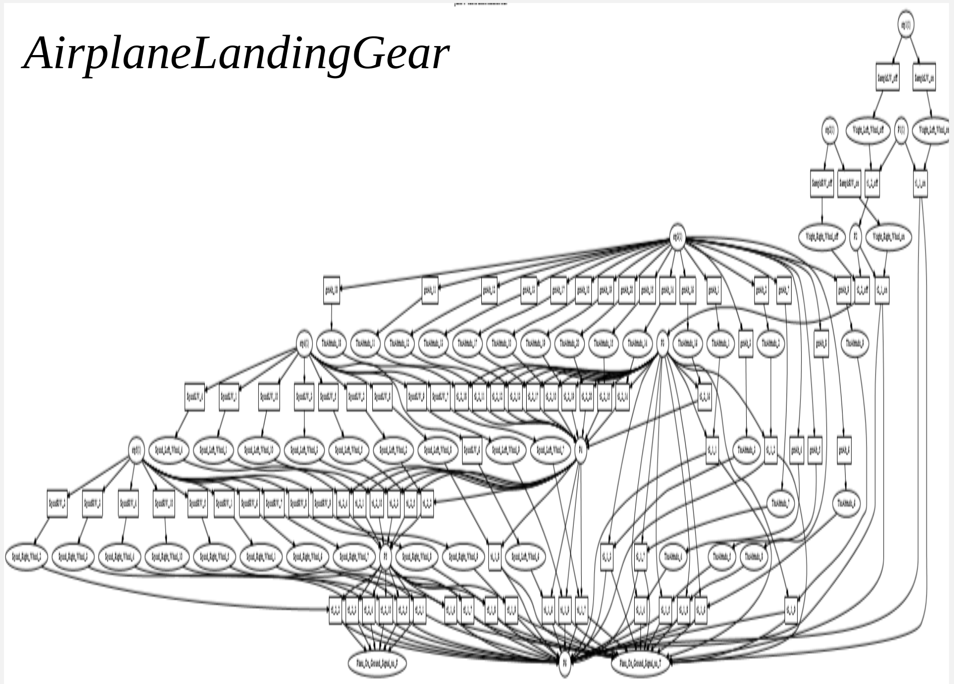

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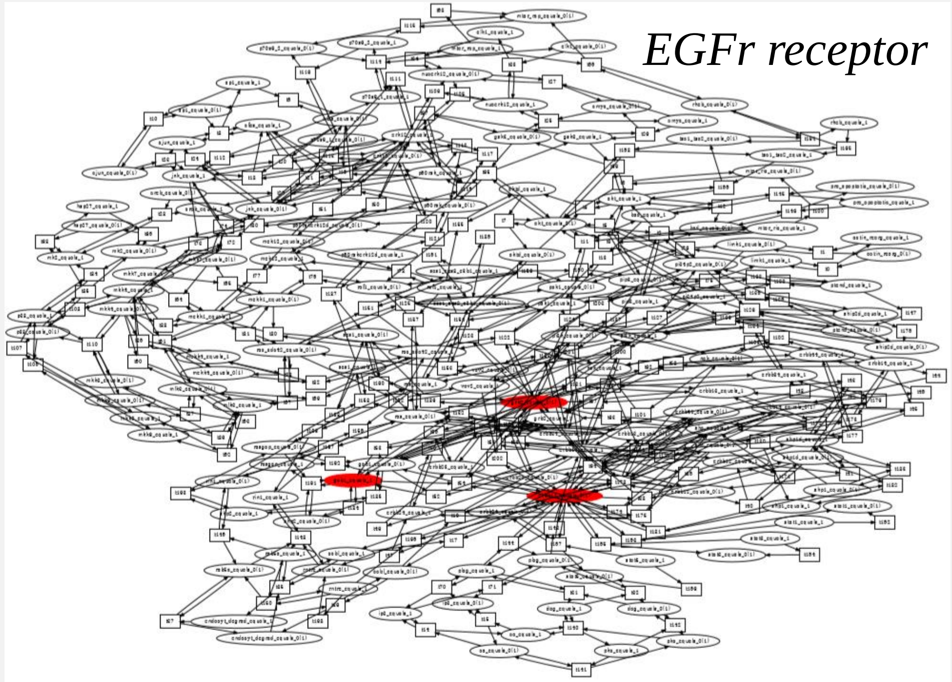

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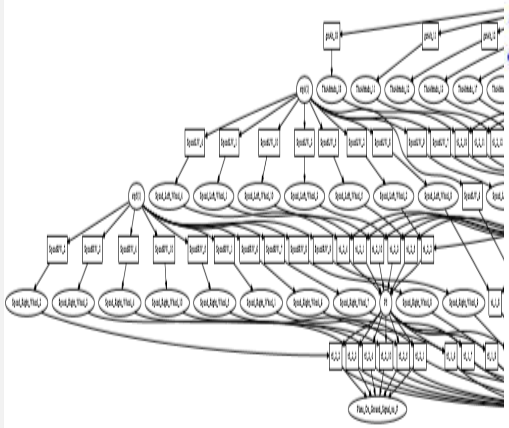
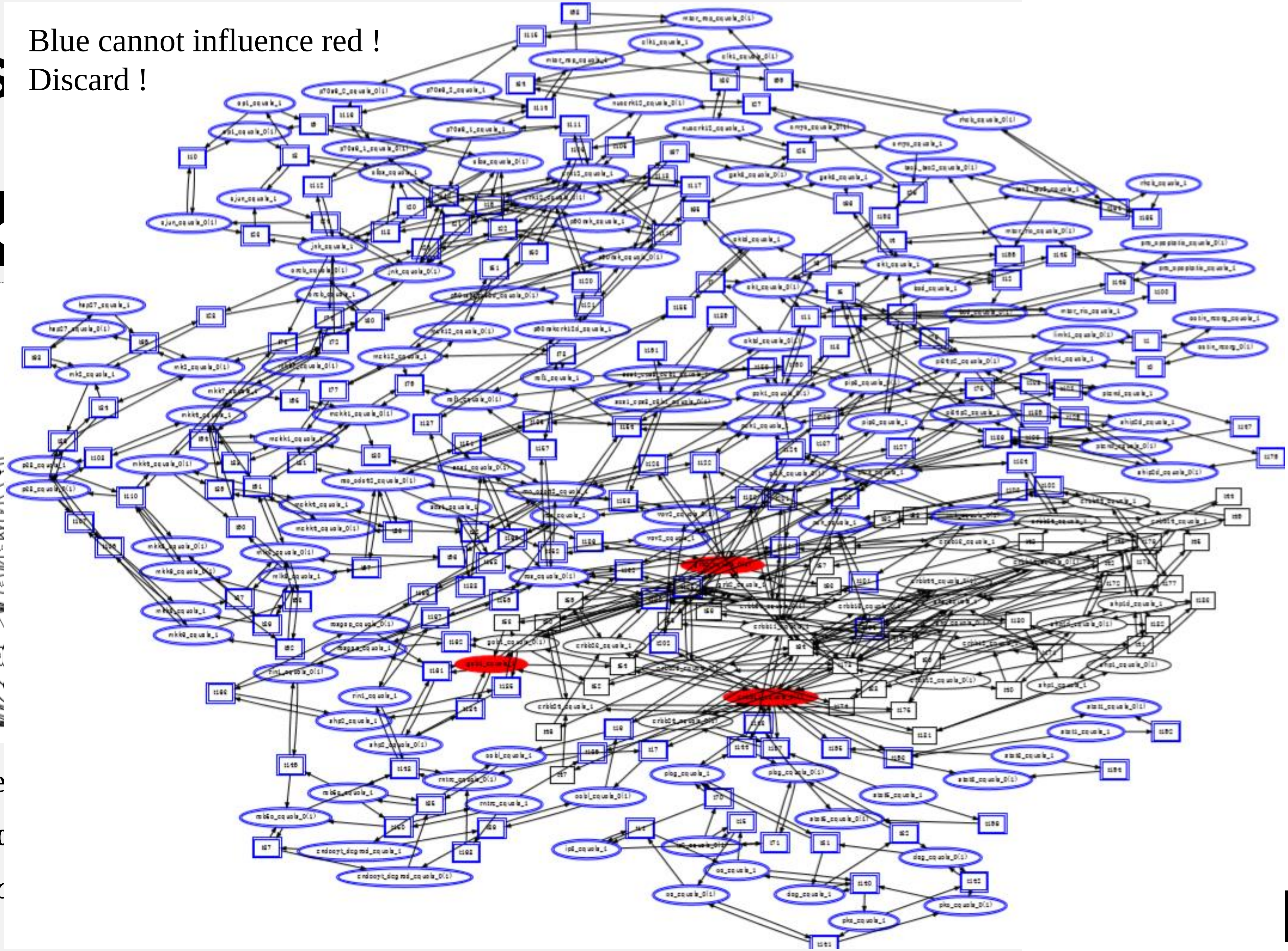
PROPERTY S

Properties of interest

Deadlock Detecti

AirplaneLandingGear





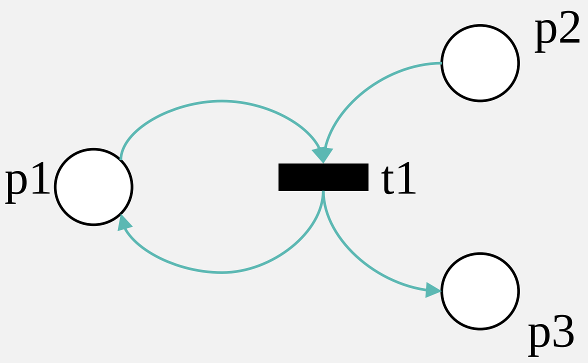
Can a deadlock state be re

=> Existence of **at least c**

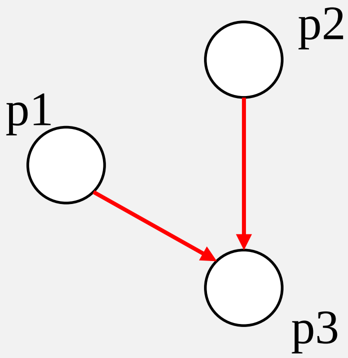
Specific rules preserving c

GRAPH BASED RULES

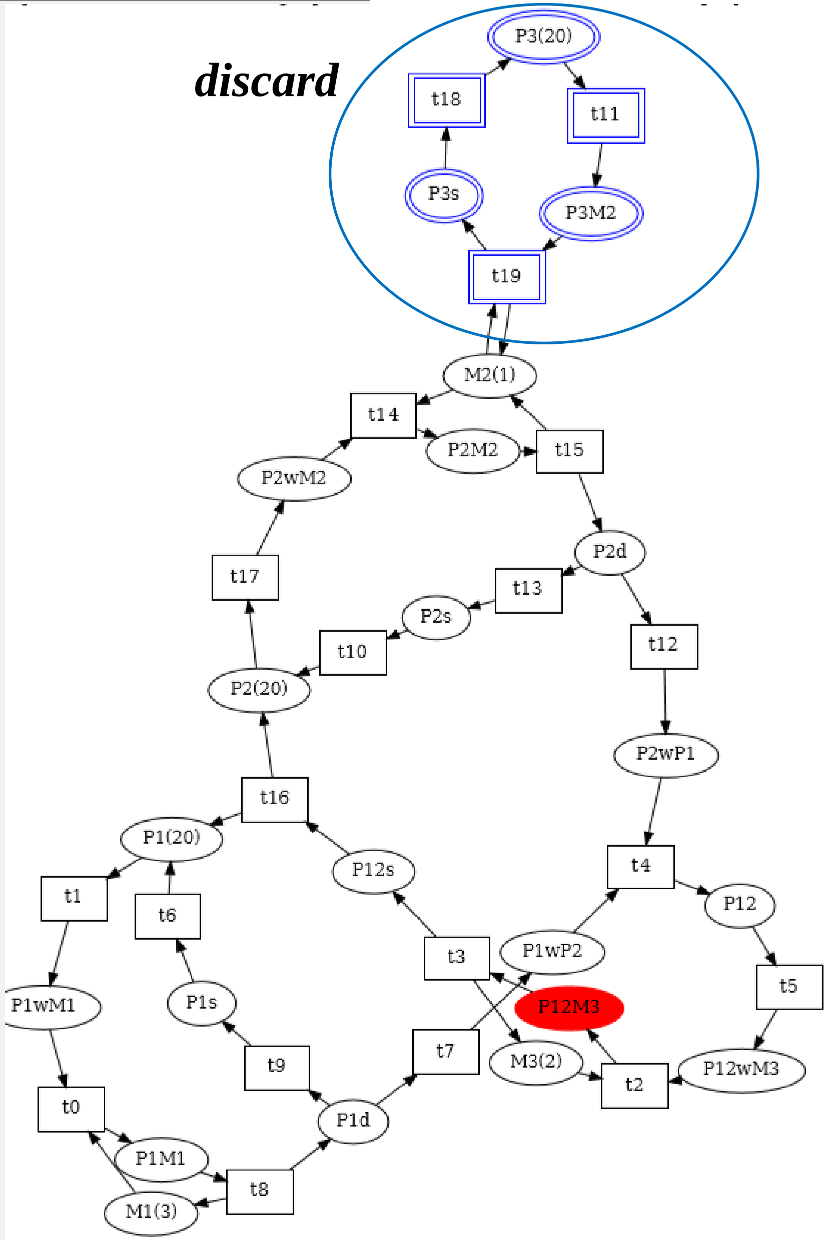
Reason on an abstraction of the net structure



Petri net



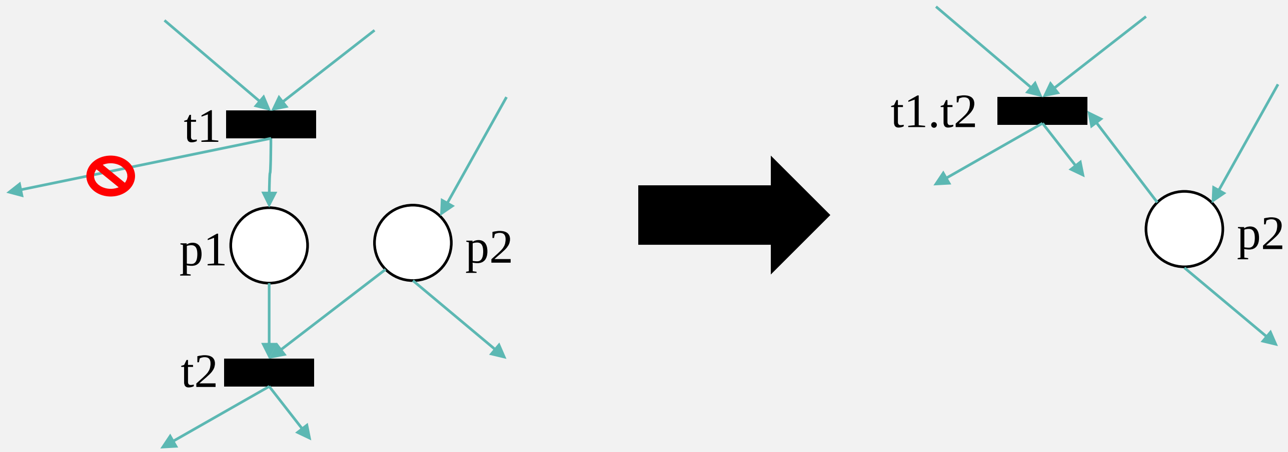
Safety Influence graph



- Compute the *prefix* in the *influence* graph of places in the support of the property
- **Brutally discard** places and transitions outside this prefix
- Two variants of the rule
  - For Deadlocks focus on SCC of the graph and their prefix :
    - side effect : if there are no SCC, the net contains deadlocks.
  - For Safety, focus on places in the support
    - Assymetric effect of read arcs : Places that ***are controlled by*** the places of interest are *not* interesting

« FREE » AGGLOMERATION

Safety preserving agglomeration



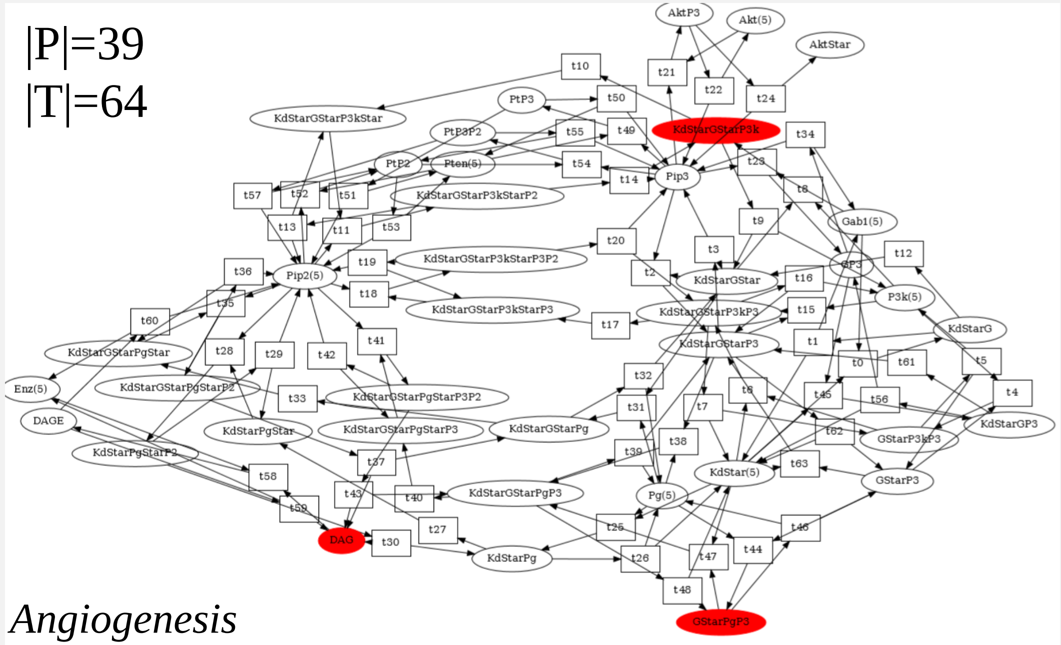
t1 single output **p1** and **t1** stutters

- Two cases :
  - If **t2** was actually fireable originally, **t1.t2** is still fireable, no behavior is lost
  - If **t2** *was not* fireable, now **t1.t2** is not fireable, so we lost the possiblity of firing **t1** ; but
    - **t1** *stutters*
    - **t1** can only feed **p**, so firing **t1** is *weakening* the rest of the net
- Free-agglomeration preserves safety but not deadlocks
    - Firing **t1** and then being unable to fire **t2** can lead to a deadlock.

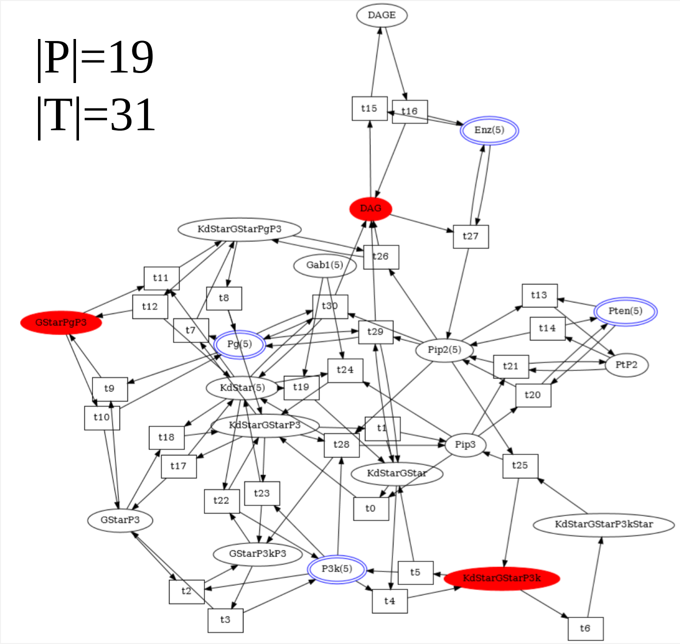
STRUCTURALLY IMPLICIT PLACE

Rules leveraging SMT over-approximation

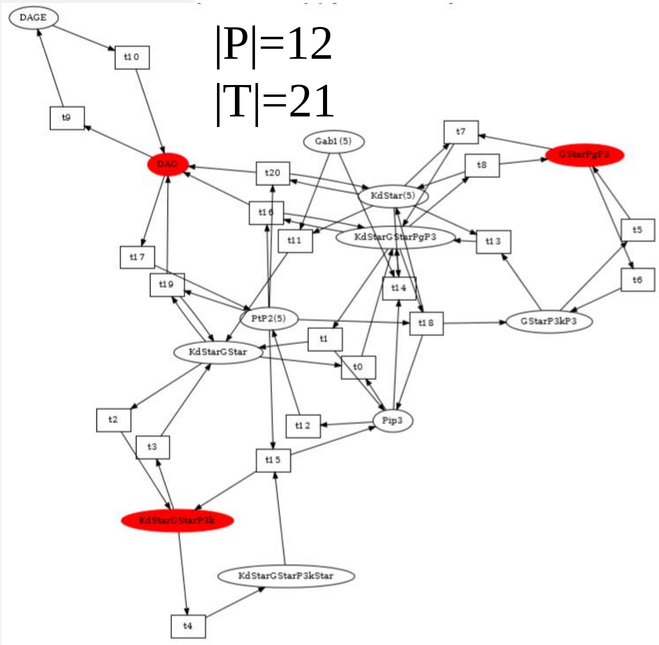
Initial model



Convergence no SMT



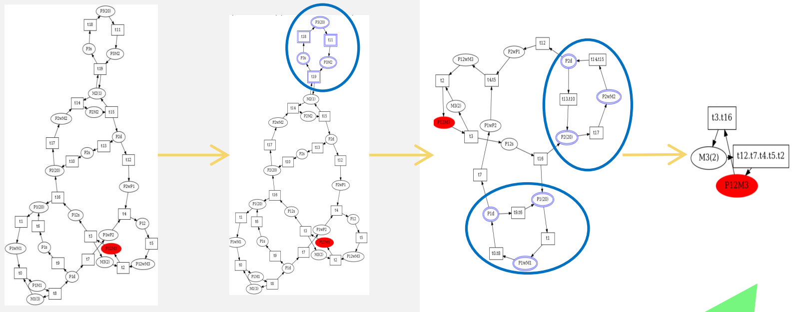
Final model



- A place is *structurally implicit* iff. it never prevents any transition from firing
  - In any marking, if a transition **t** consuming from **p** is enabled without considering **p**, then **p** *always* contains enough tokens to fire **t**
  - Build an SMT problem, asserting this invariant
  - Discard **p** if the invariant can be proved
- Can help start another round of reductions
  - Powerful test though more costly than most rules
  - Covers variants of « redundant place » rules in e.g. Berthelot.

STRUCTURAL REDUCTION RULES

Highlights



- Total of 22 rules presented in the paper
- Basic rules :
  - equal places, constant place, sink place, …
  - neutral transition, dominated transition…
- Advanced rules :
  - Unmarked Syphon, Future equivalent places, token movement
- Agglomeration based rules :
  - pre and post-agglomeration,
  - new « free » agglomeration
- Graph based rules :
  - Compute SCC or a prefix of nodes in an abstraction of the net structure
  - Notion of « Prefix of interest » for deadlock and invariants
  - Fusion of « free » SCC
- Structural reductions supported by SMT over-approximation
  - Structurally dead transitions
  - Structurally implicit places

+preserves properties of interest
+memory and time efficient
+simplifies the net for any analysis
+synergy with over/under approximations
+leverage SMT component for more reduction power

EVALUATION

Validation with Model-Checking Contest 2019 nets and formulas

- Examination = (model + 16 invariants) or (model + deadlock)
  - Select all examinations with known results in 2019 (produced by *any* tool) :
  - **90** model families, **2680** examinations, **28 900** properties
  - Max runtime 12 minutes, 8GB RAM
    - 21/2680 : **0.008 %** timeout
    - On average **31 seconds** per examination
- Deadlocks :
  - 902 / 932 : **96.8 %** solved
- Invariants :
  - 1634 / 1748 : **93.5 %** fully solved all 16 invariants
  - 27594 / 27968 : **98.6 %** of formulas solved
- Resulting nets when not fully solved are much smaller

CONCLUSION

Structural Reductions Revisited

- Combine three complementary strategies
- Fully implemented and freely available as part of ITS-Tools http://ddd.lip6.fr
- Competing as a « filter » within the model-checking contest in « its-tools » and « its-lola »
- Full graphical examples used in this presentation

  https://lip6.github.io/ITSTools-web/structural