Alpine Verification Meeting 2013, FBK, Trento, Italy.

Optimization Techniques For Craig Interpolant Compaction In Unbounded Model Checking

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Before starting..

- Talk in part based on a paper we presented at DATE 2013 Conference:

Gianpiero Cabodi, C. Loiacono, D. Vendraminetto.
Optimization techniques for craig interpolant compaction in unbounded model checking.
DATE 2013: 1417-1422

Outline

- Motivations & background
  - *Hardware designs verification*
  - Craig Interpolants in MC
  - ITP size compaction & scalability
- Contributions
  - Redundancy removal and reduction of
    - UNSAT proofs
    - Craig interpolants
  - Heuristic procedure for scalable ITP compaction
- Experimental results & Conclusions

Motivations

- Can ITPs compete with IC3 ?

IC3	ITP
2-level (AND-OR) characteristic functions	Multiple level circuits
Single instance of TR	TR unrollings

- Main limitations of ITP
  - BMC-based model (vs. cube/clause-based reachability)
  - ITPs are highly redundant

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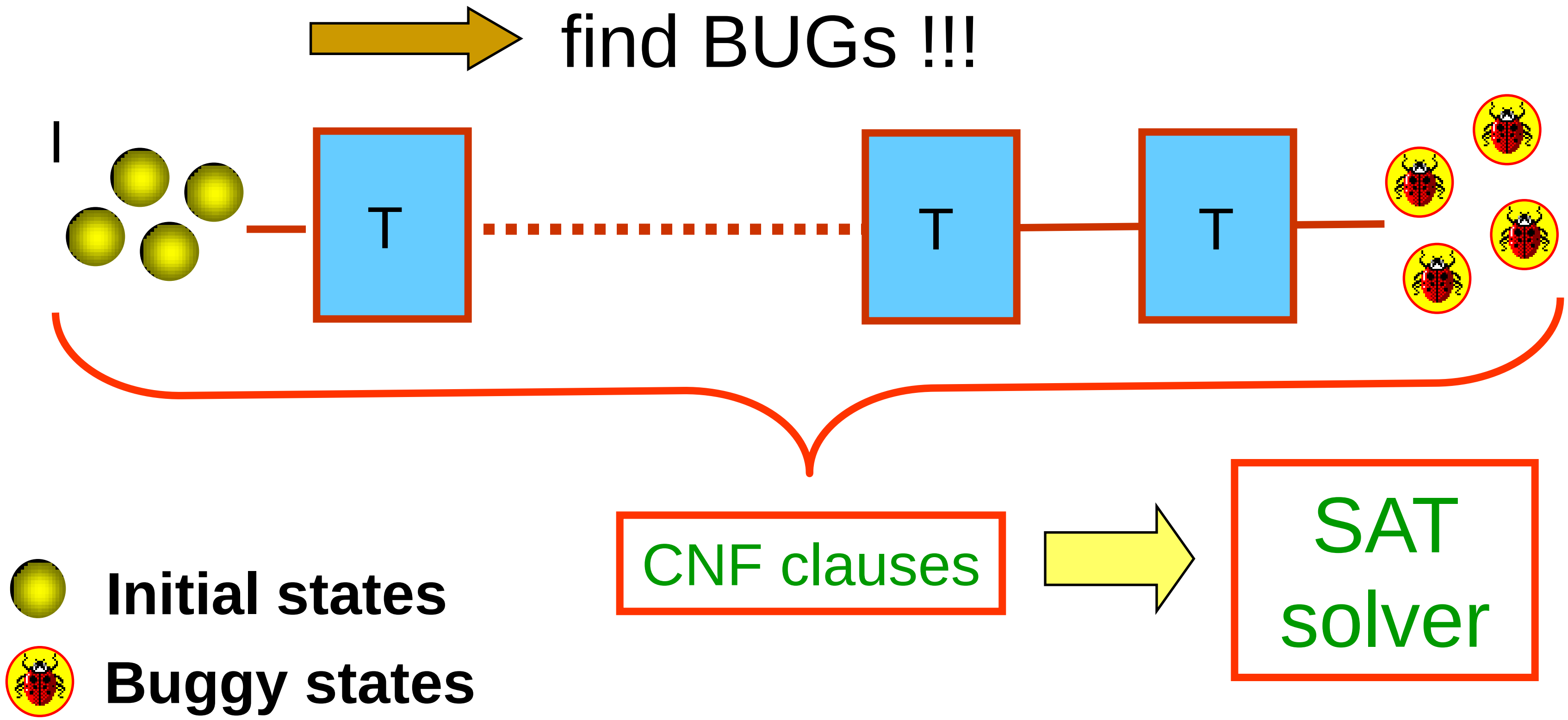
  - <u>ITPs are highly redundant</u>

Bounded Model Checking

- Trading off completeness for productivity



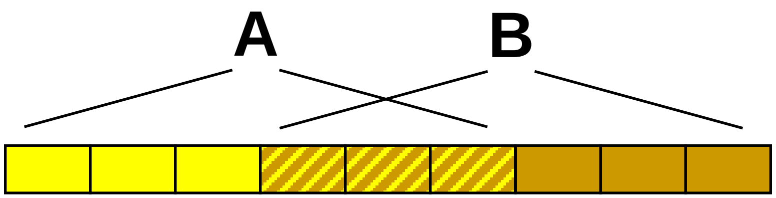
Interpolation [Craig'57]

- Given $A \wedge B = 0$
- A' = *interpolant*(A,B)
  - $A \Rightarrow A'$
  - $A' \wedge B = 0$
  - A' refers only to common variables of A,B
- Interpolants from proofs
  - Given a resolution refutation of $A \wedge B$
  - A' is derived in linear time and space [Pudlak,Krajicek'97]

Interpolation [McMillan'03]

- Interpolant as over-approx. image operator
  - Over-approximation
  - Variable quantification
- Works whenever a representation of *backward reachable* space is given
  - A: From $\wedge$T (FWD)
  - B: paths to failure states (BWD)
  - A': over-approx image
- Approx image is called *adequate* w.r.t. B

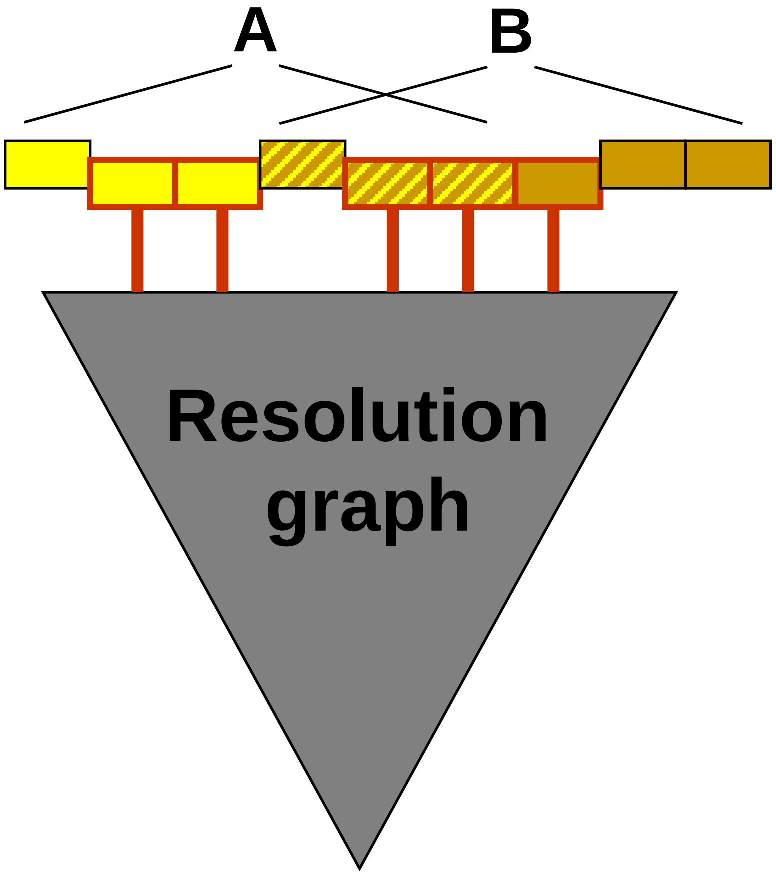
ITP from refutation proof



CNF clauses

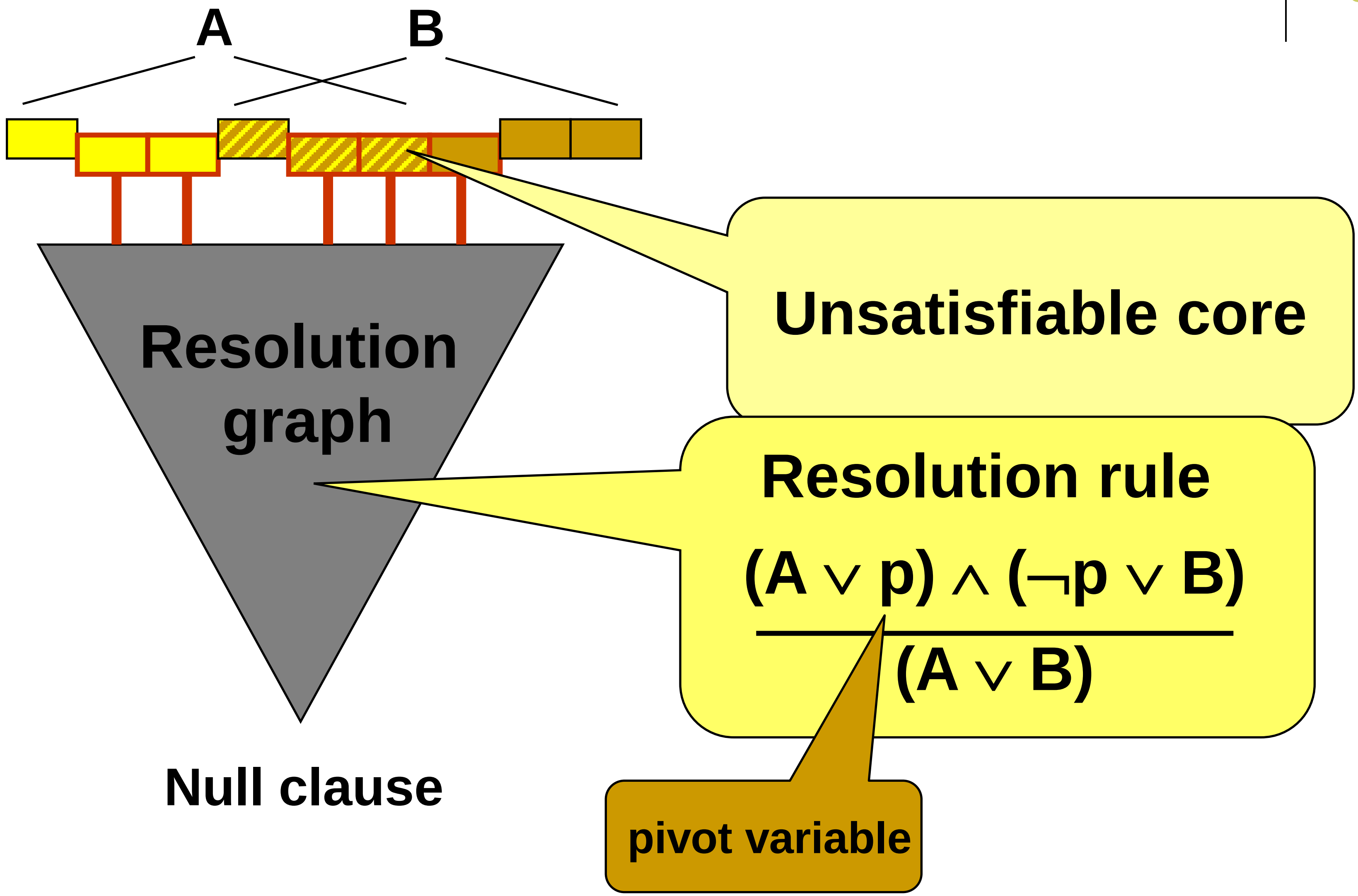
UNSAT problem ($A \wedge B = 0$)

ITP from refutation proof

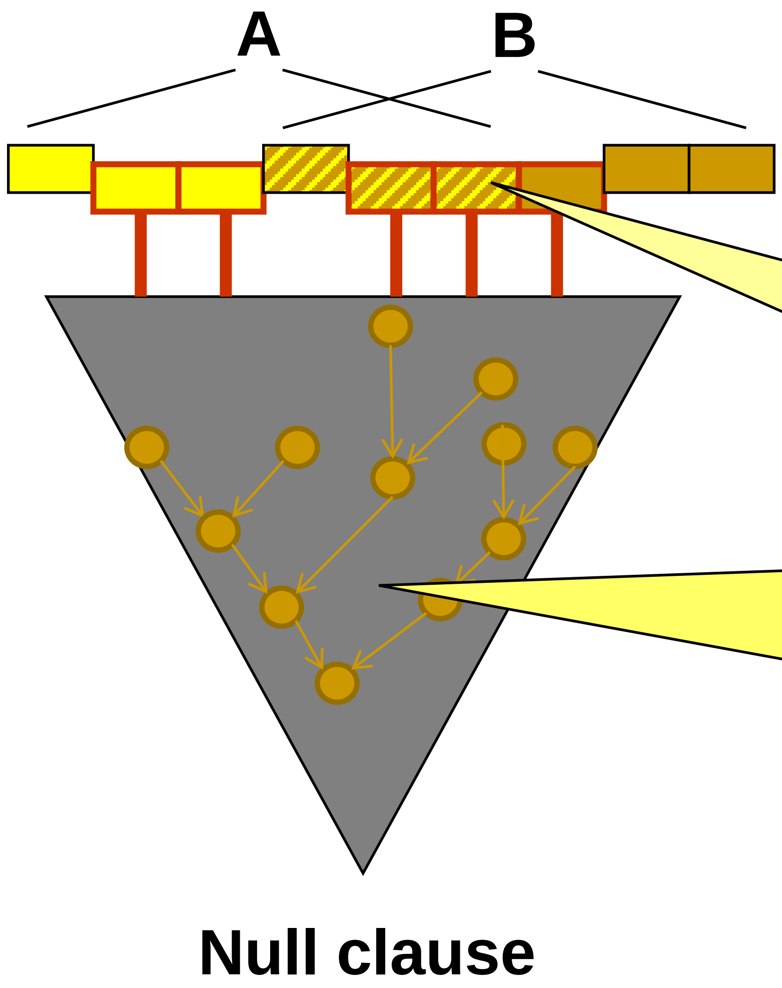


Null clause

ITP from refutation proof



ITP from refutation proof

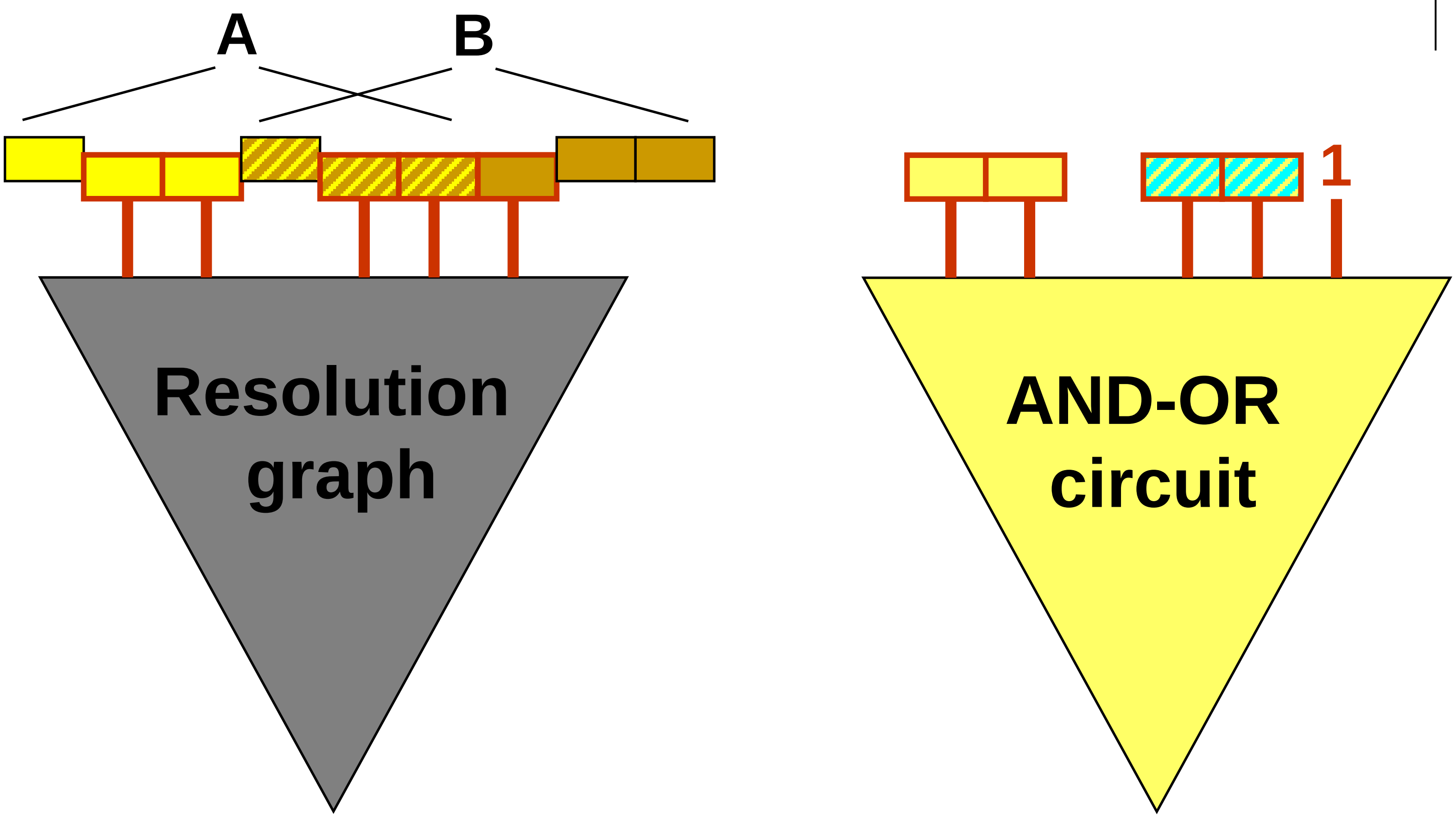


Unsatisfiable core

Resolution rule

$$\frac{(A \vee p) \wedge (\neg p \vee B)}{(A \vee B)}$$

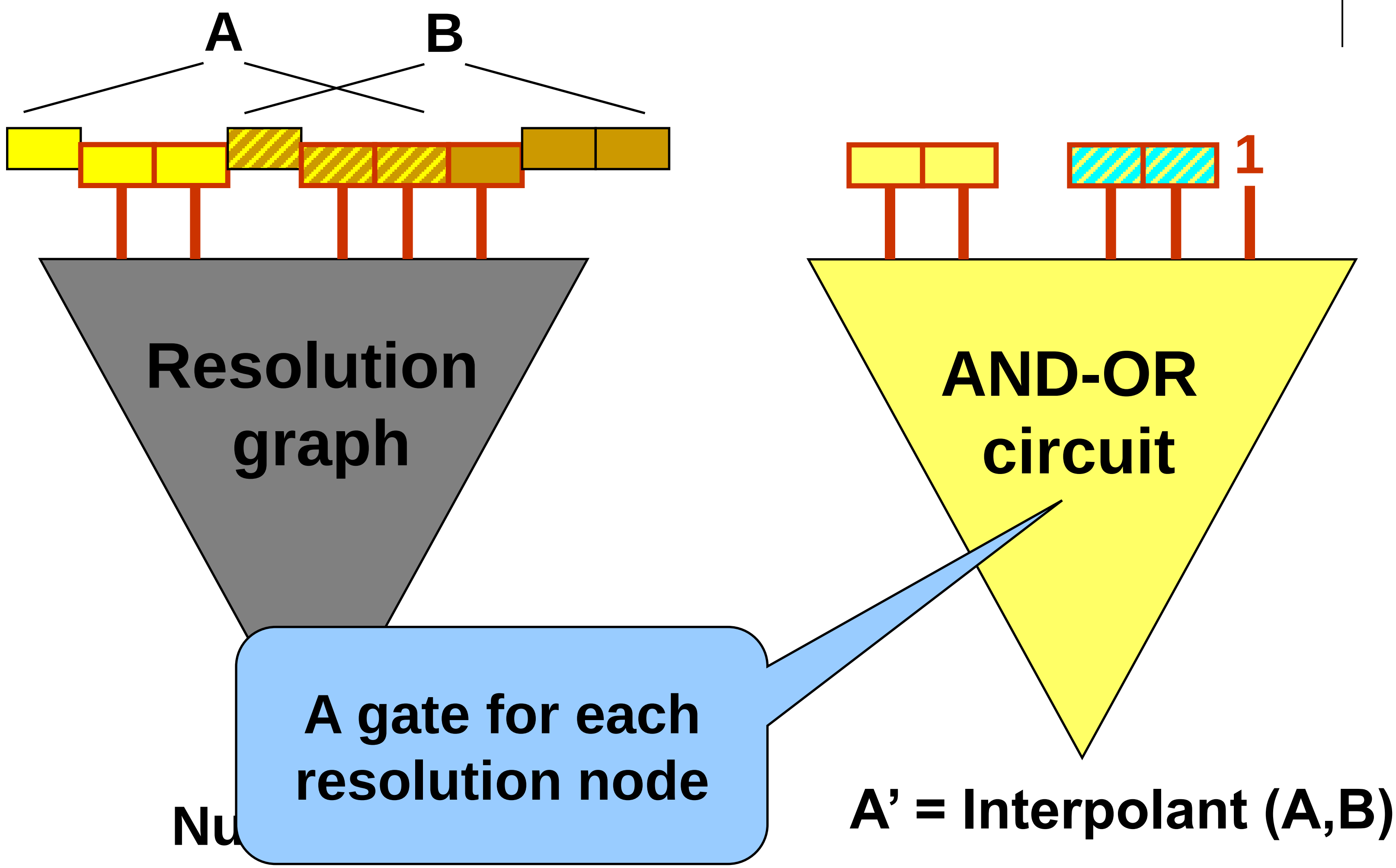
Interpolant from refutation proof



Null clause

A’ = Interpolant (A,B)

Interpolant from refutation proof

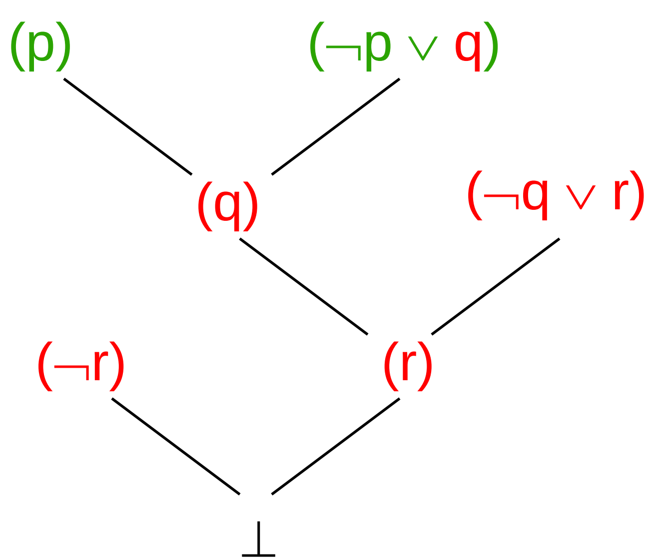


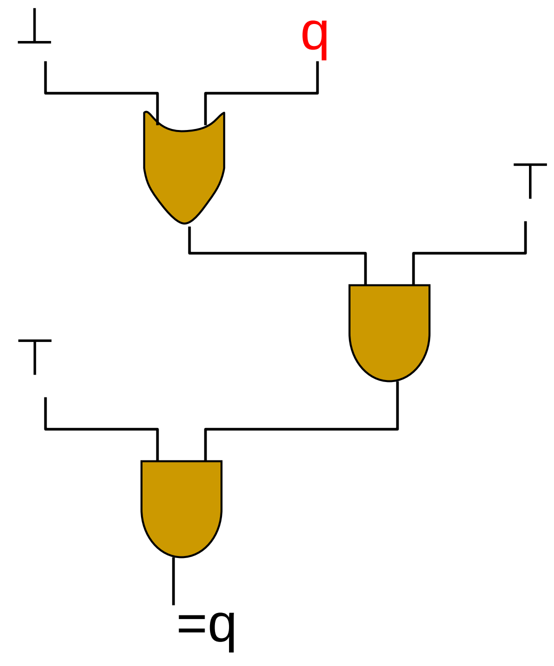
Interpolant rules

- Interpolation is a circuit that follows the *structure* of the proof

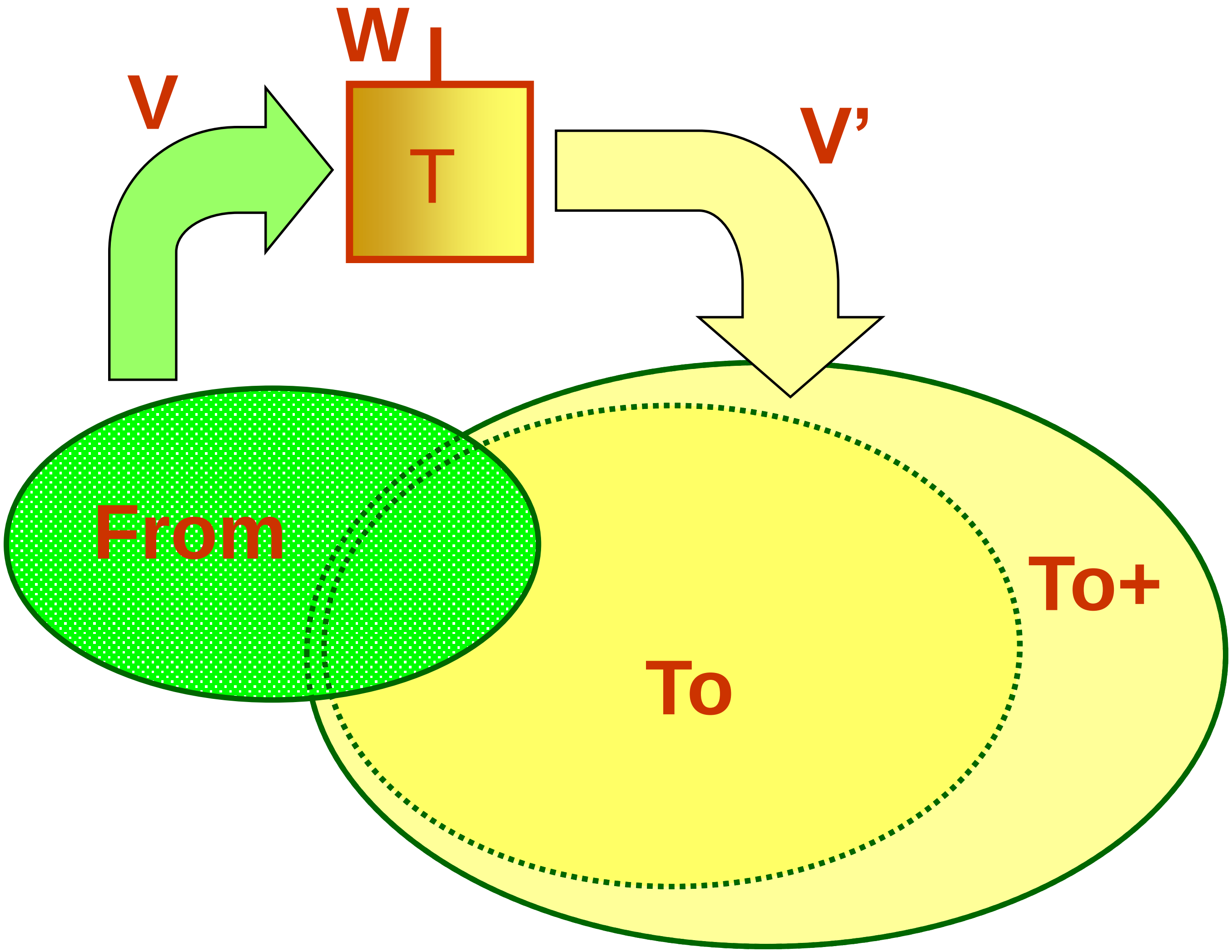
$A = (p)(\neg p \vee q)$

$B = (\neg q \vee r)(\neg r)$



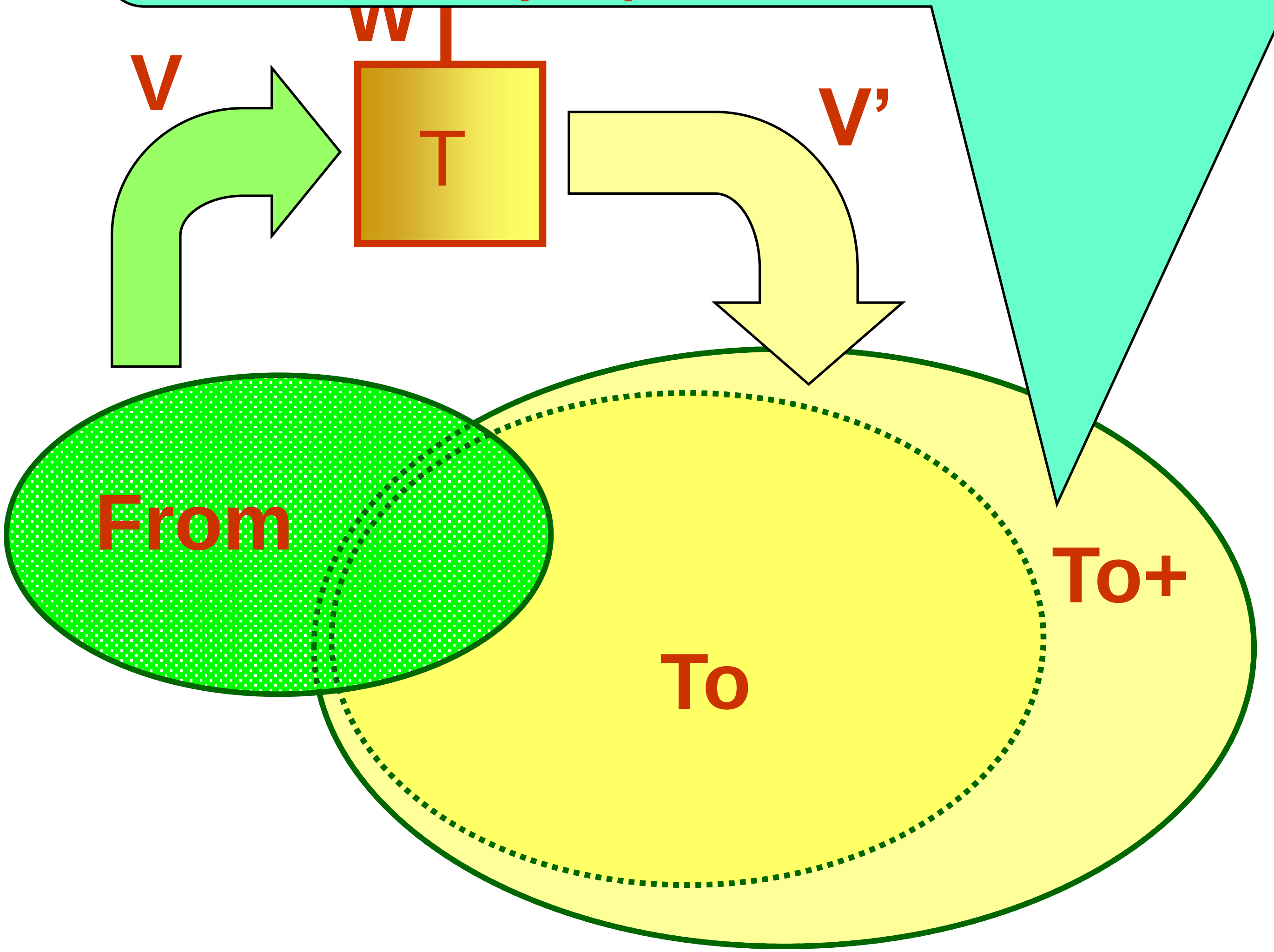


Image+

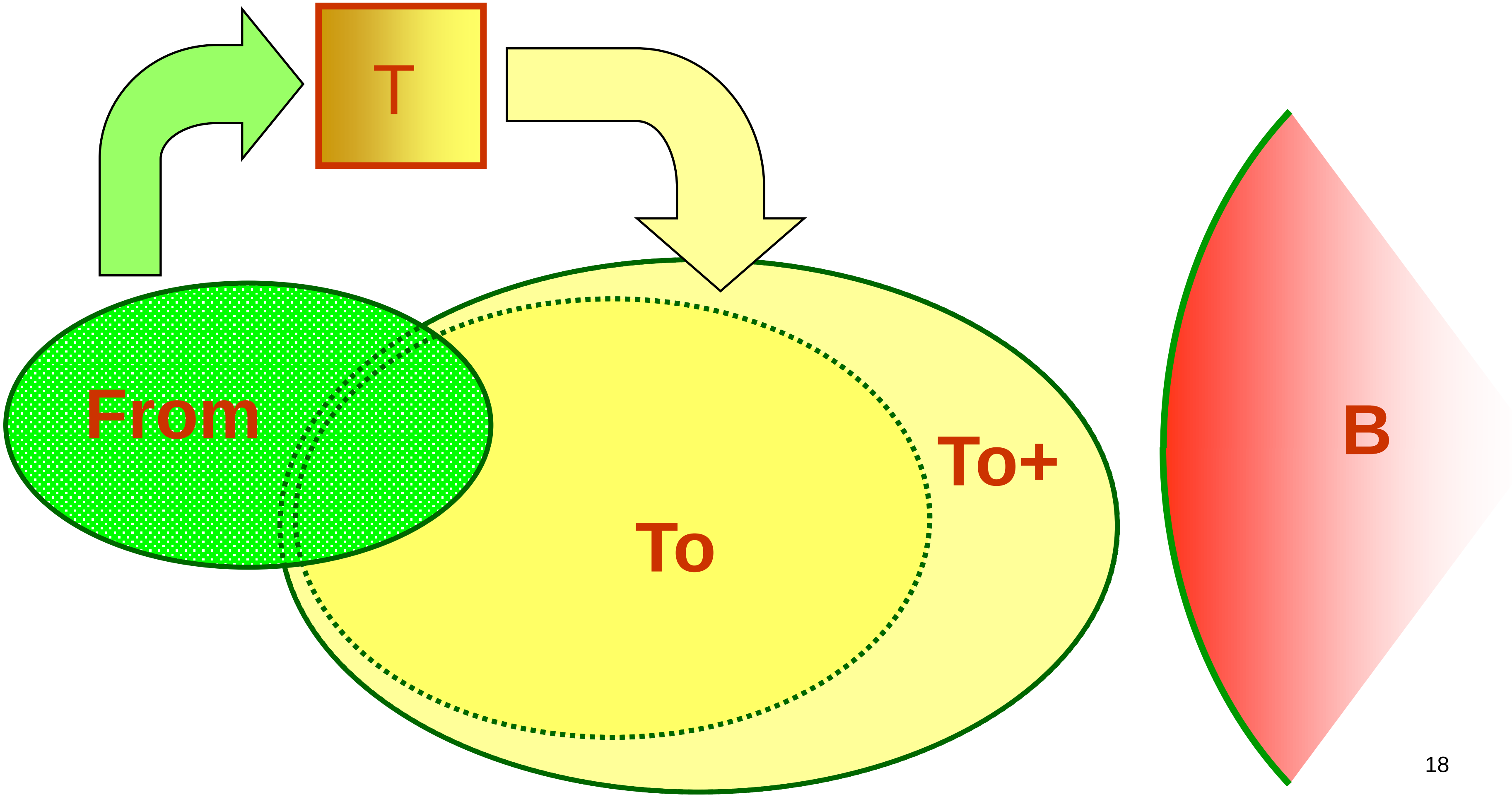


Image

$$To+(V') = IMG+(From,T) = Approx(\exists_{(V,W)} From(v) \wedge T(V,W,V'))$$



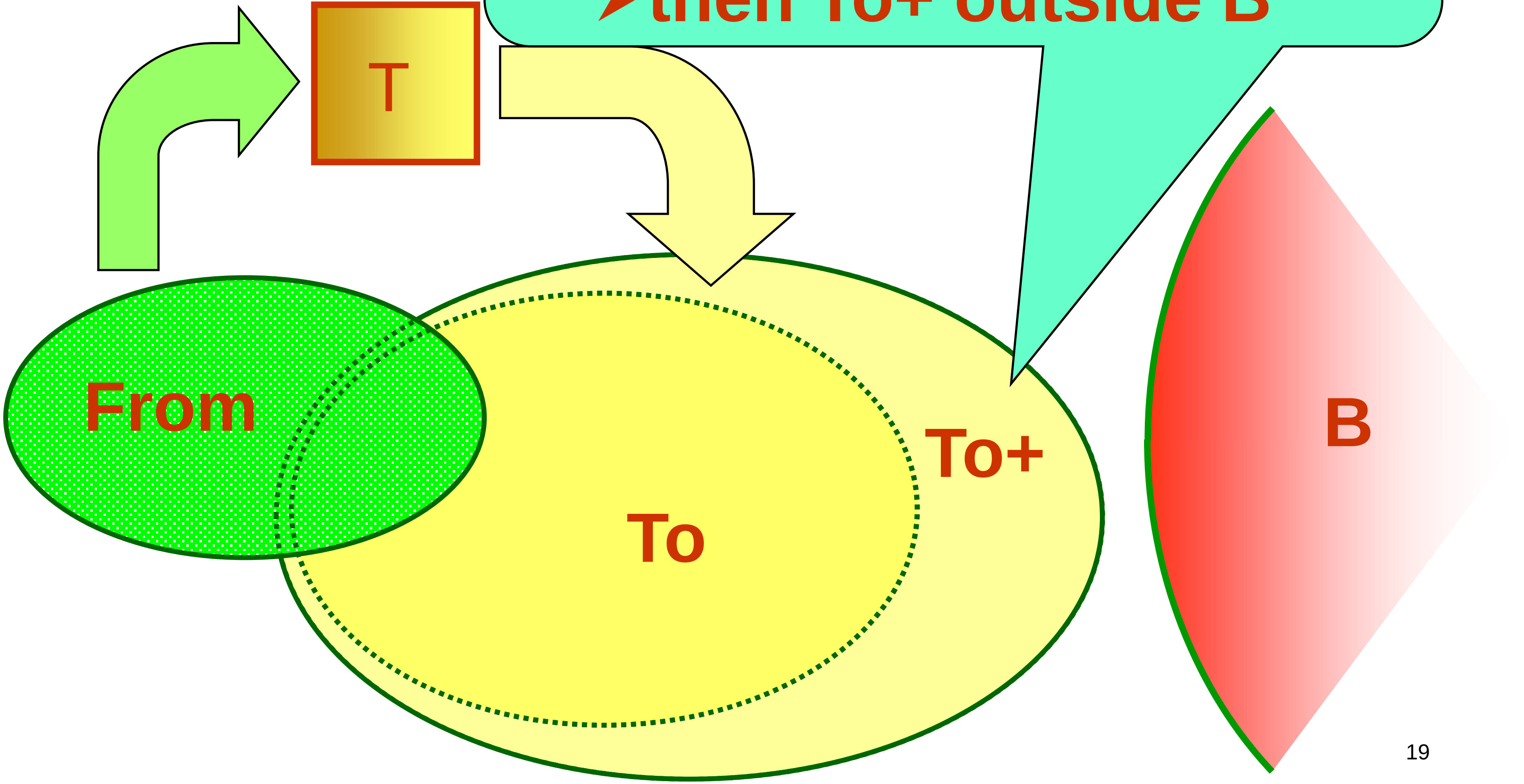
Adequate Image+



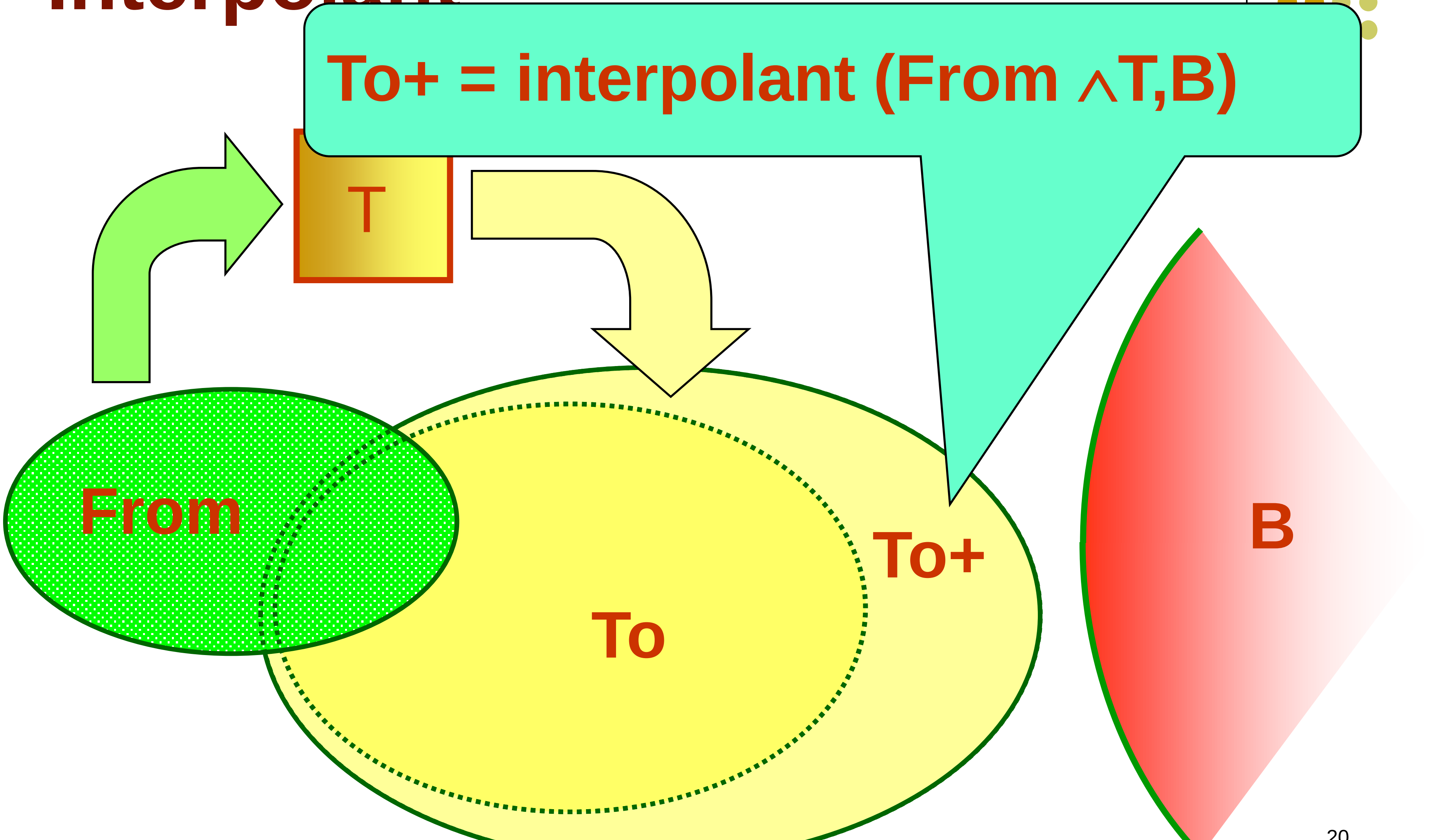
Adequate I

To+ adequate w.r.t. B

- **if To outside B**
- **then To+ outside B**

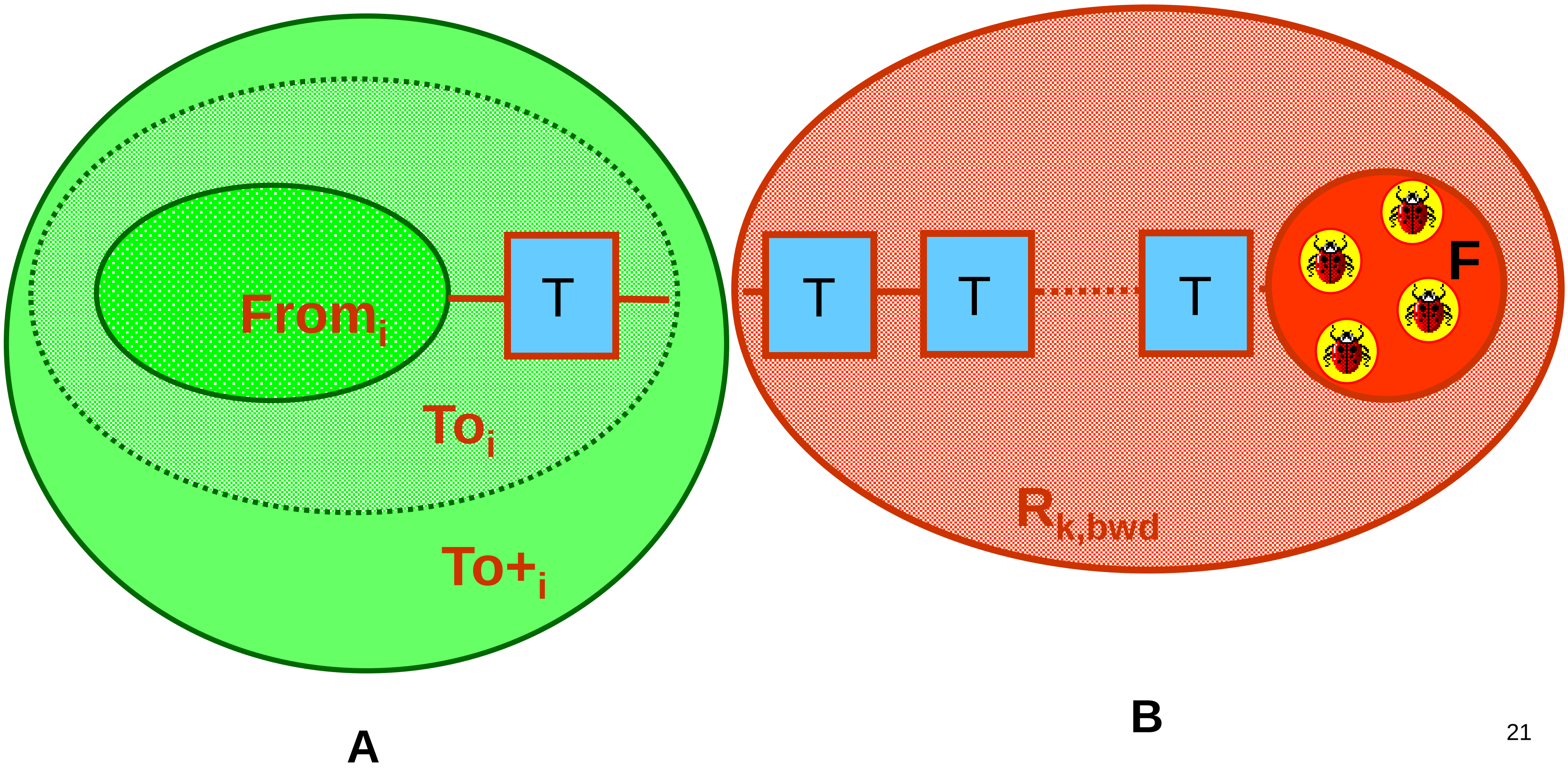


Adequate Image+ by Interpolant



ITP

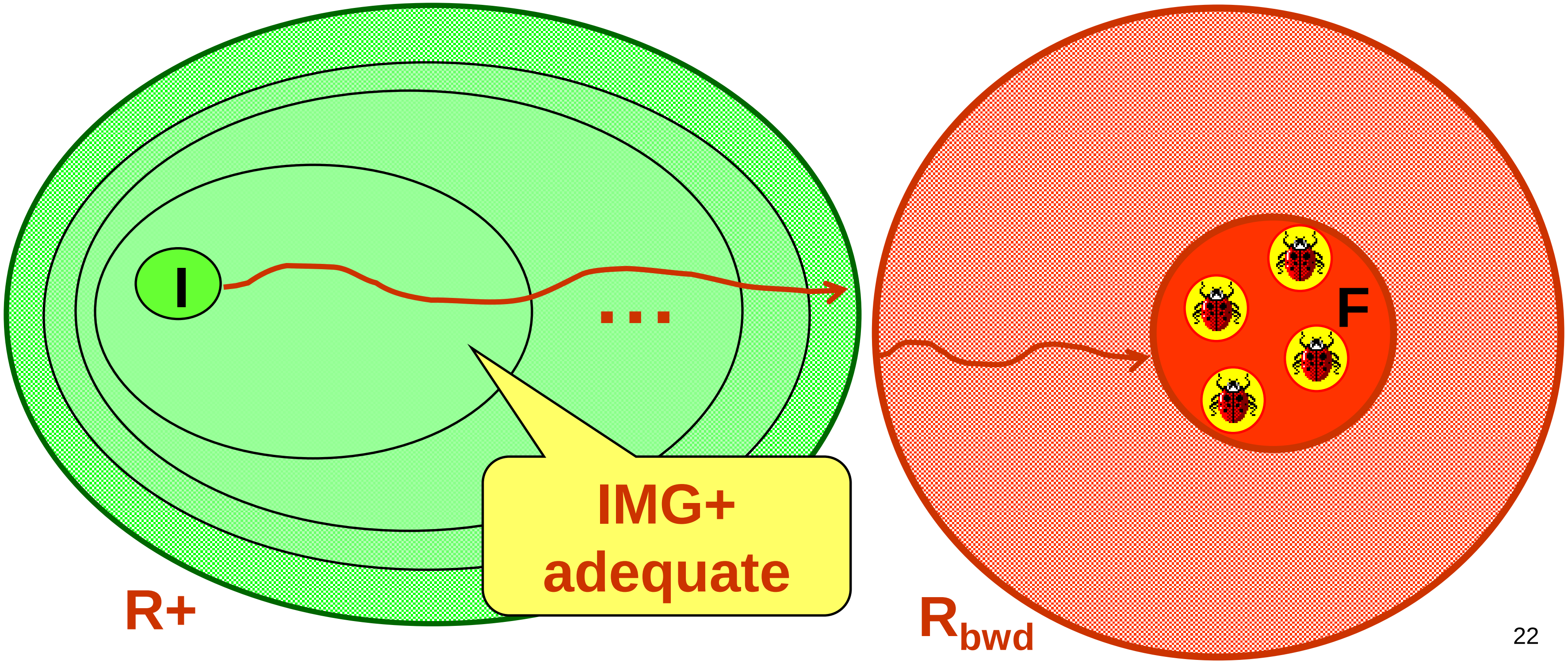
Standard ITP: $to+_i$ computed from appr. $From_i$



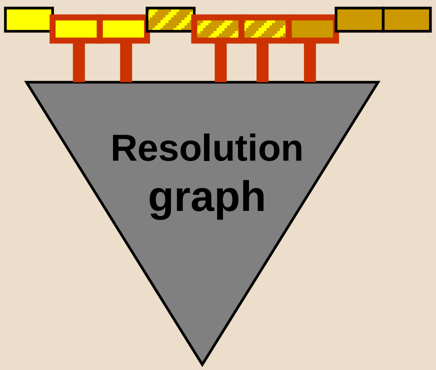
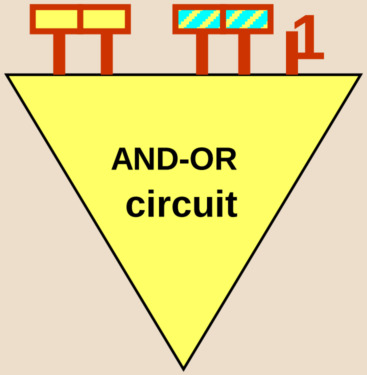
Why use adequate IMG+ ?

⇒ FWD *approximate* reachable states

- computed by adequate IMG+
- do not intersect BWD reachable states



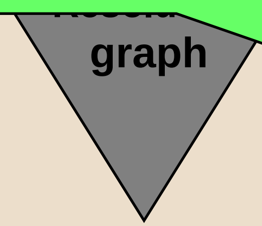
ITP compaction

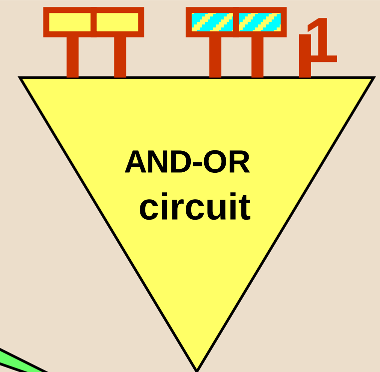
Proof reduction	ITP circuit compaction	
		
Alternative proofs • different resolution schemes	BDD/SAT sweeping	Const propagation
Equivalent proofs • redundancy removal	ODC	Refactor rewrite

ITP compaction

Problem #1:

- **SCALABILITY**





	ITP circuit compaction	
Alternative proofs • different resolution schemes	BDD/SAT sweeping	Const propagation
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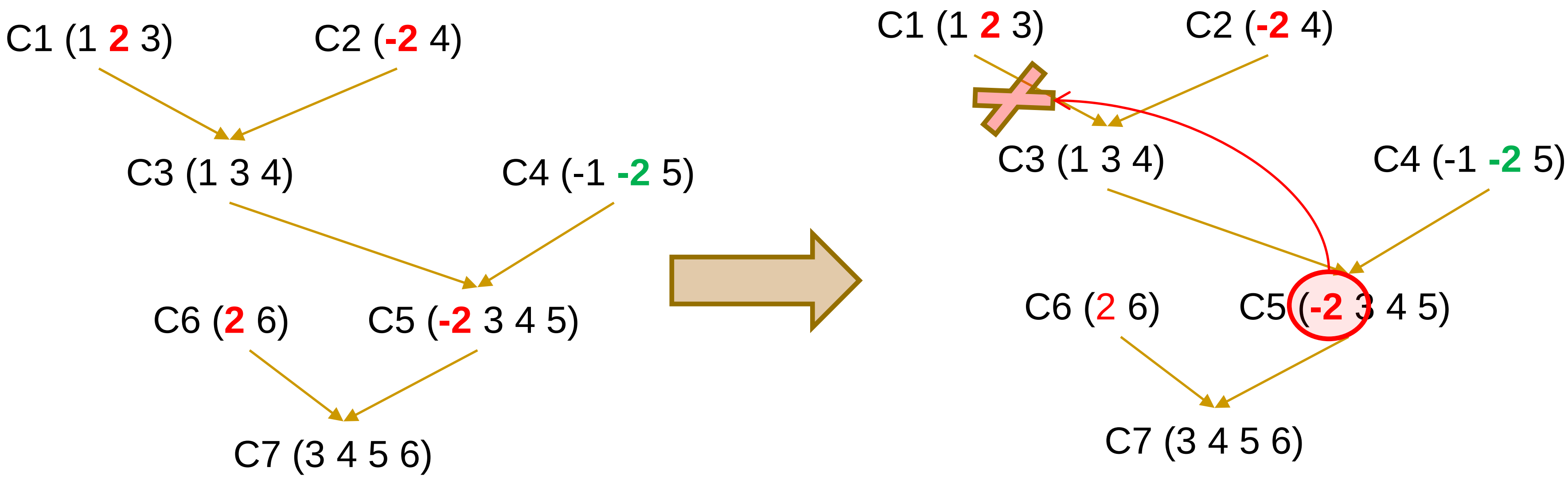
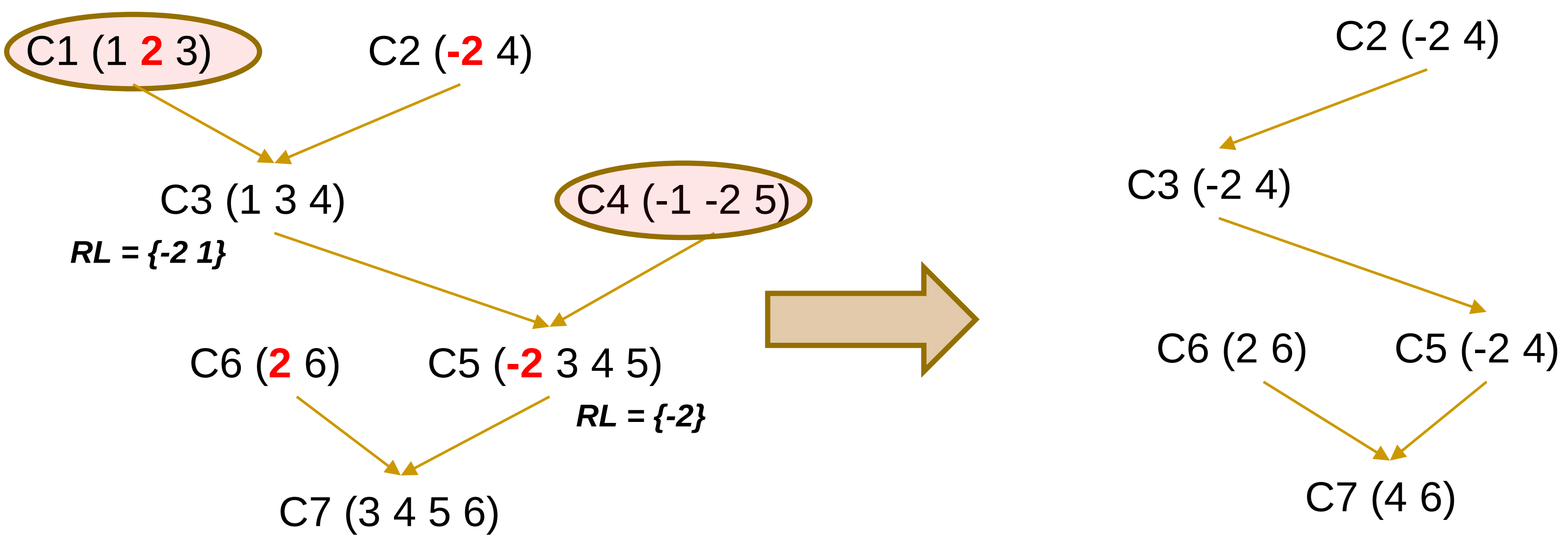
Proof reduction

- Recycle-pivots [Bar-Inal & al. HVC08]



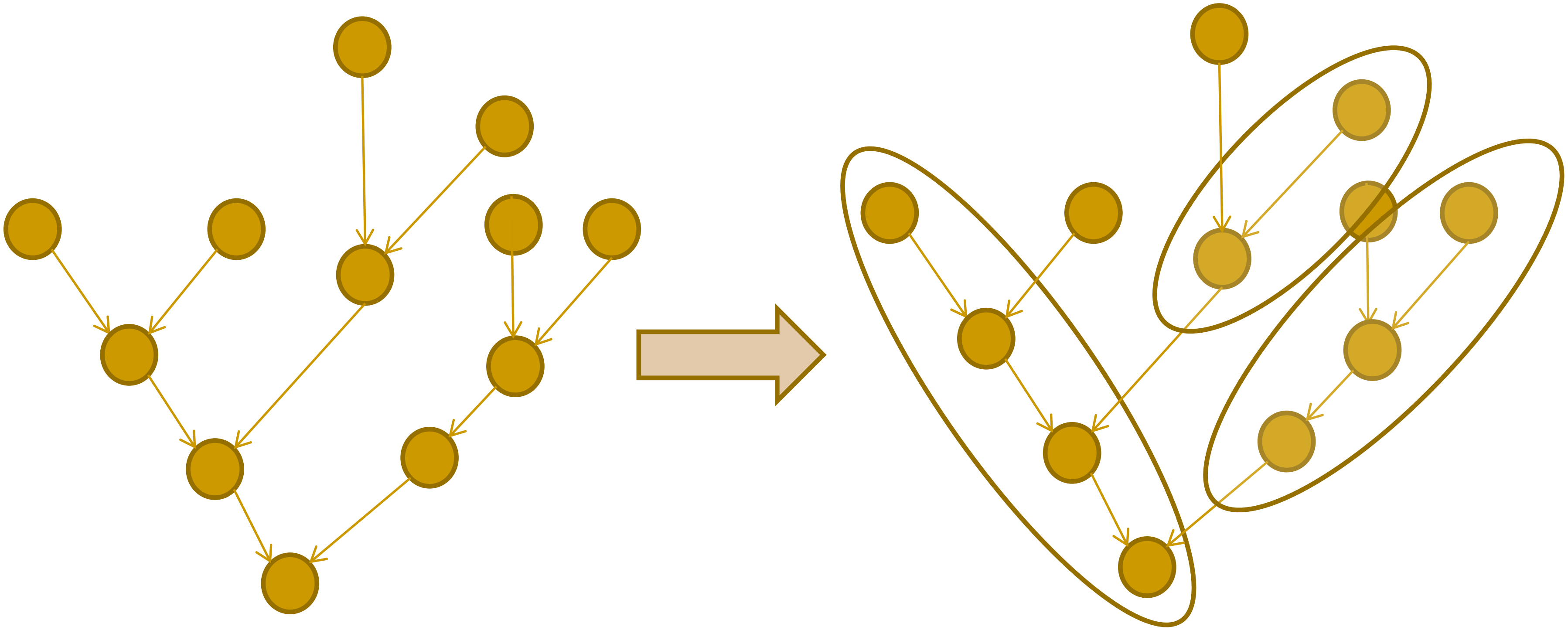
Proof reduction

- Recycle-pivots + restruct proof [Bar-Inal & al. HVC08]



R*L denotes the Removable-Literals*

Our Contribution: exploit proof *topology*



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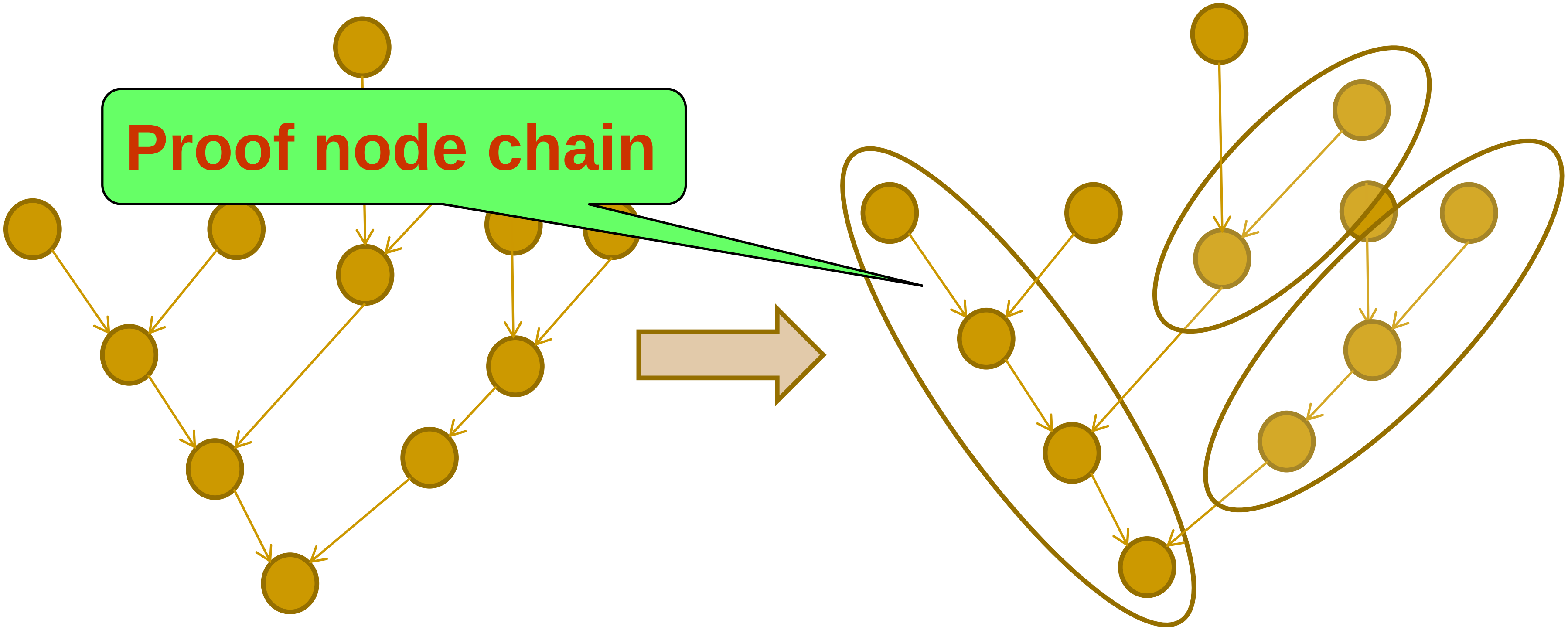


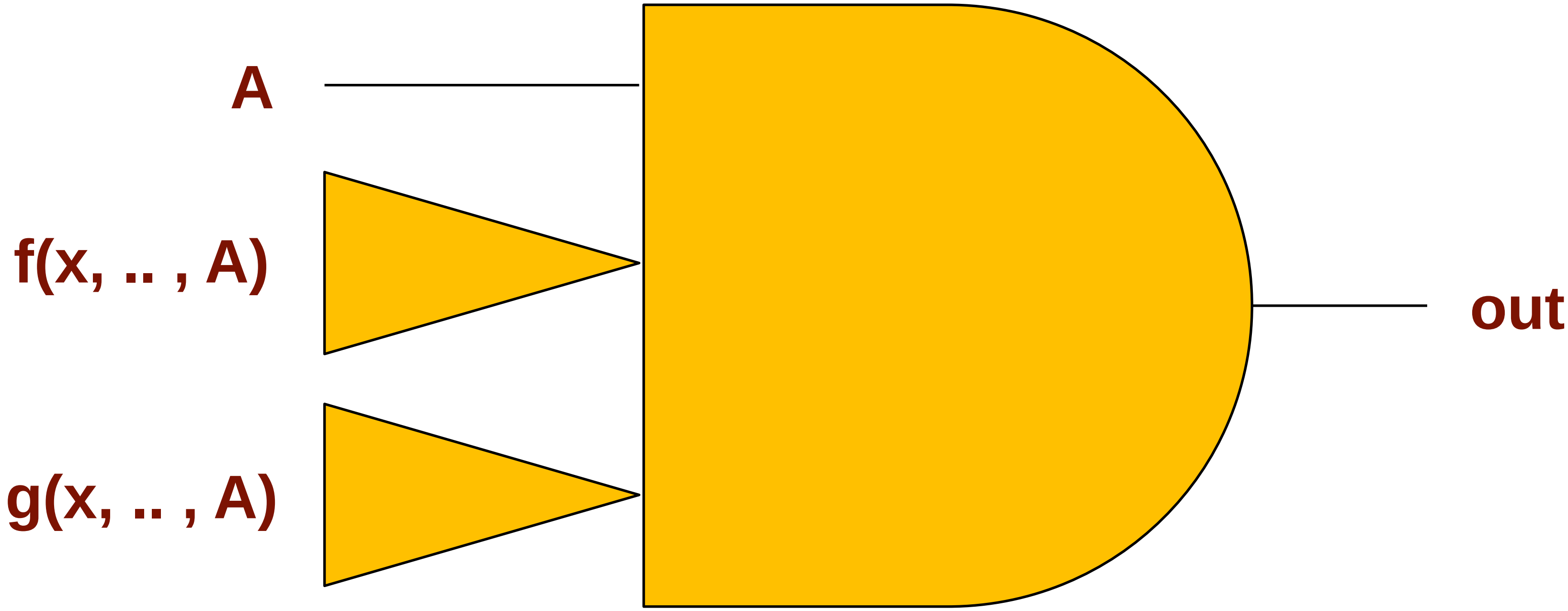
- Simpler data structure for proof reduction algorithms and further techniques

ITP Circuit Compaction

- Logic synthesis manipulations on the proof
  - Constant propagation
  - BDD-based sweeping (for equivalences)
  - Observability Don't Care (lightweight)
- Proof into AIG
  - ODC (lightweight)
  - Logic synthesis
    - rewrite / refactor, using *ABC* tool
    - AIG balance
  - ITE-based decomposition (iff necessary)

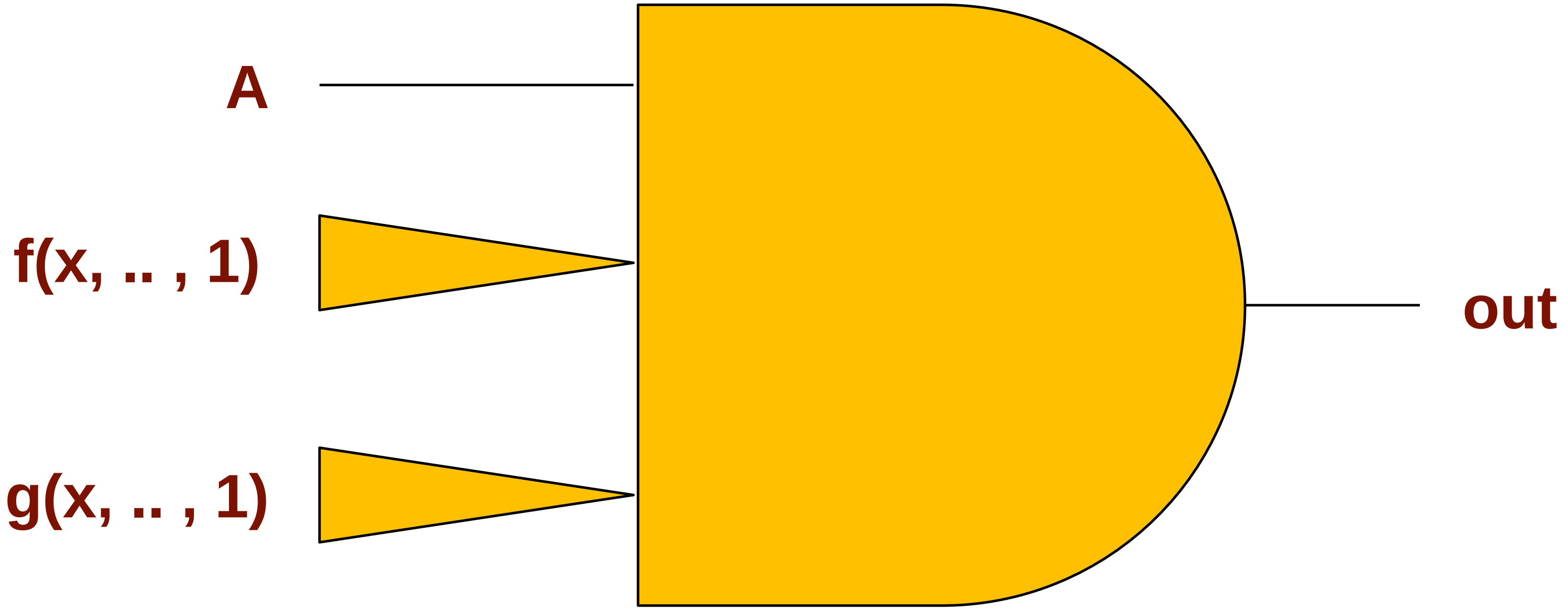
Observability don't care

- If A == 0 $\rightarrow$ out = 0 ; no matters f(.) or g(.)
  - don't-care set

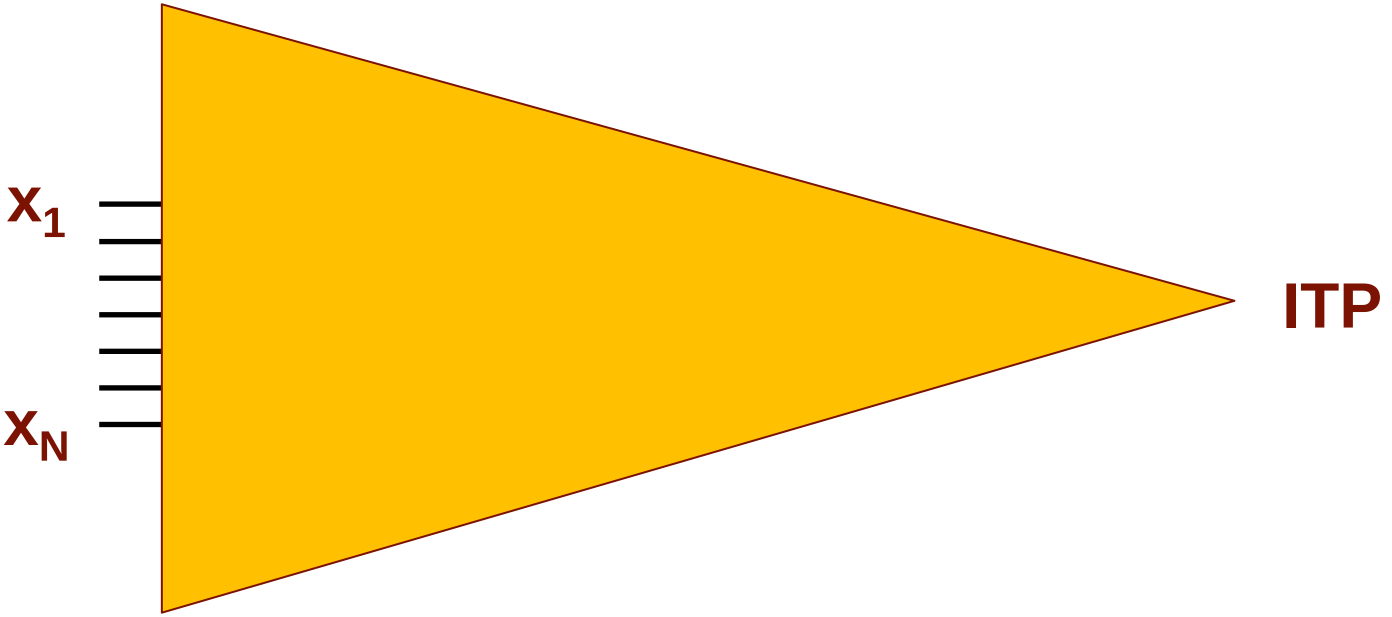


Observability don't care

- If A == 1 $\rightarrow$ f(.) and g(.) can be simplified
  - care set



ITP ITE decomposition



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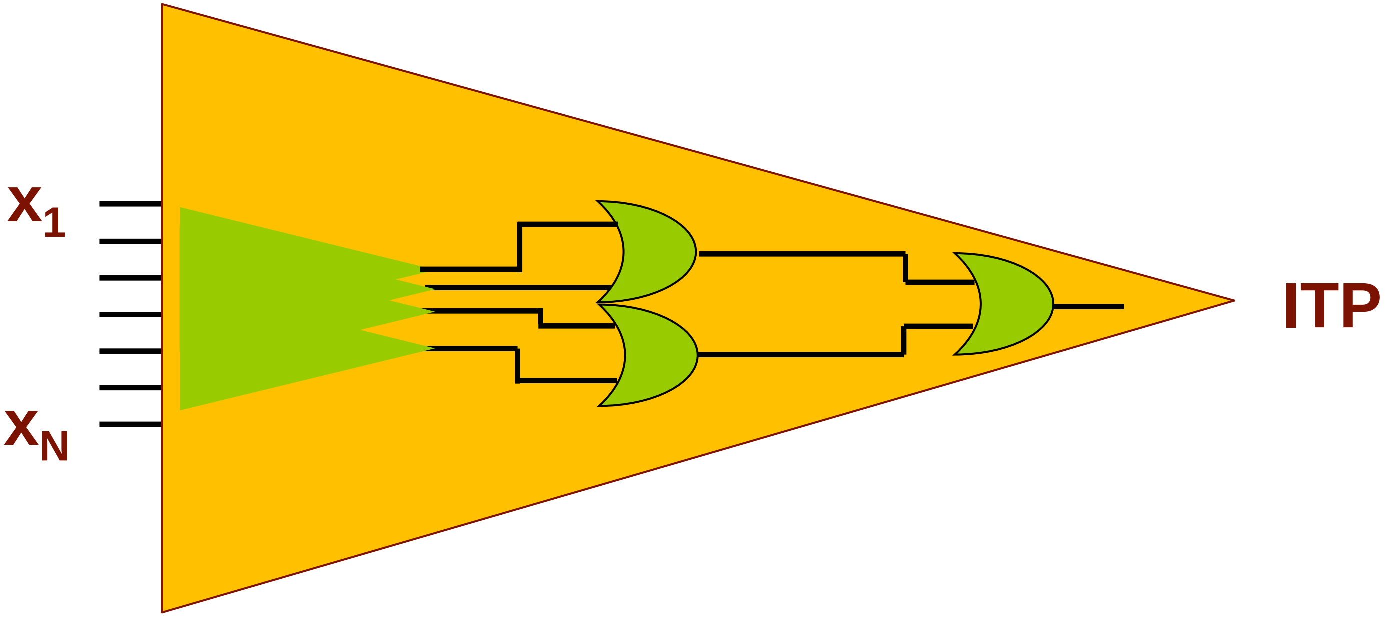

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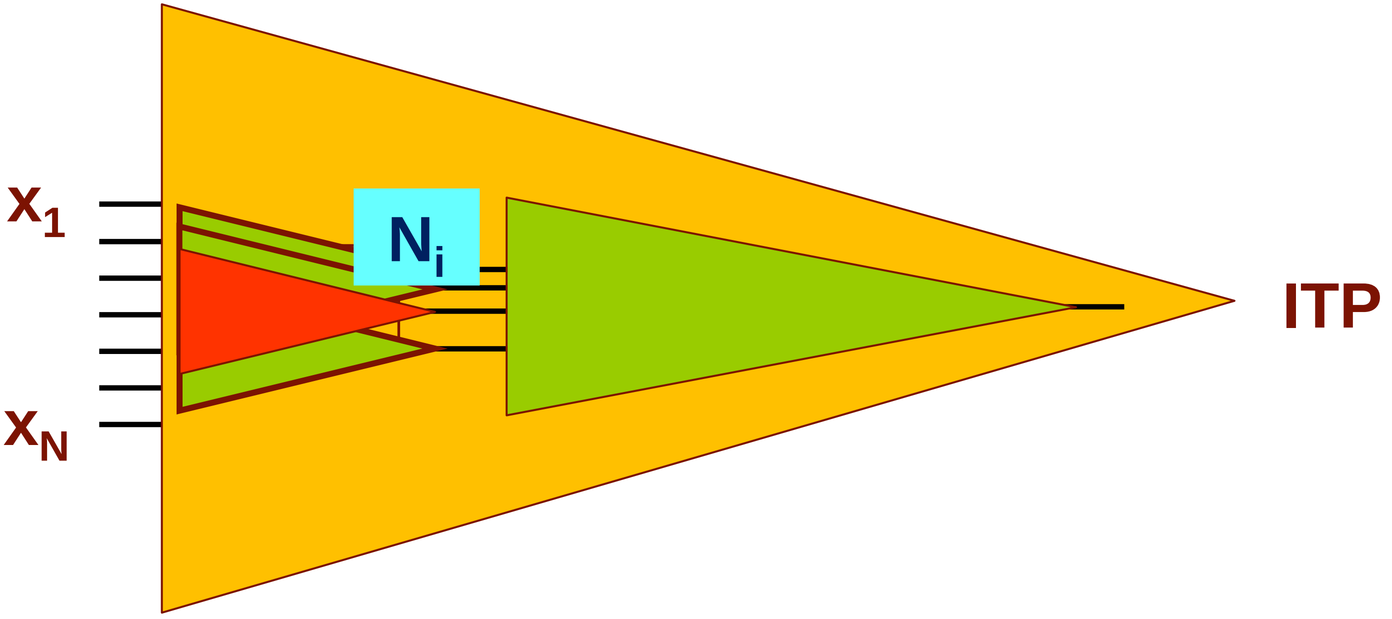

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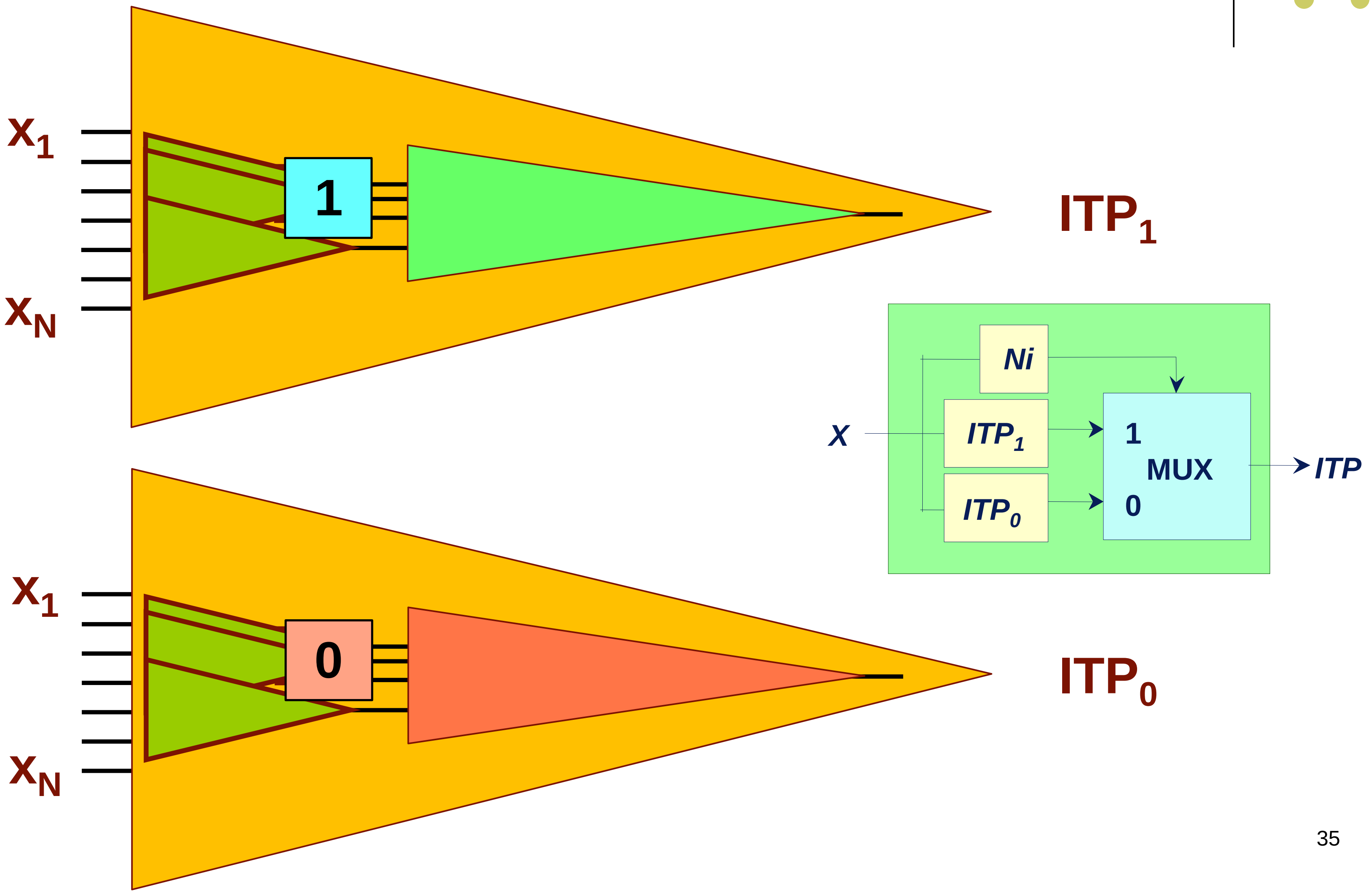


Ad-Hoc ITP compaction

AigIteDecomp (ITP)

if (max recursions || |ITP| < th)

standardLogicSynth (ITP)

do

search node N_i with highest FO

ITE(N_i,ITP_1,ITP_0) //compute cofactors; equals to ITP

if (*accept* (**ITE** decomp)) //size-based heuristic

AigIteDecomp (N_i)

AigIteDecomp (ITP_1)

AigIteDecomp (ITP_0)

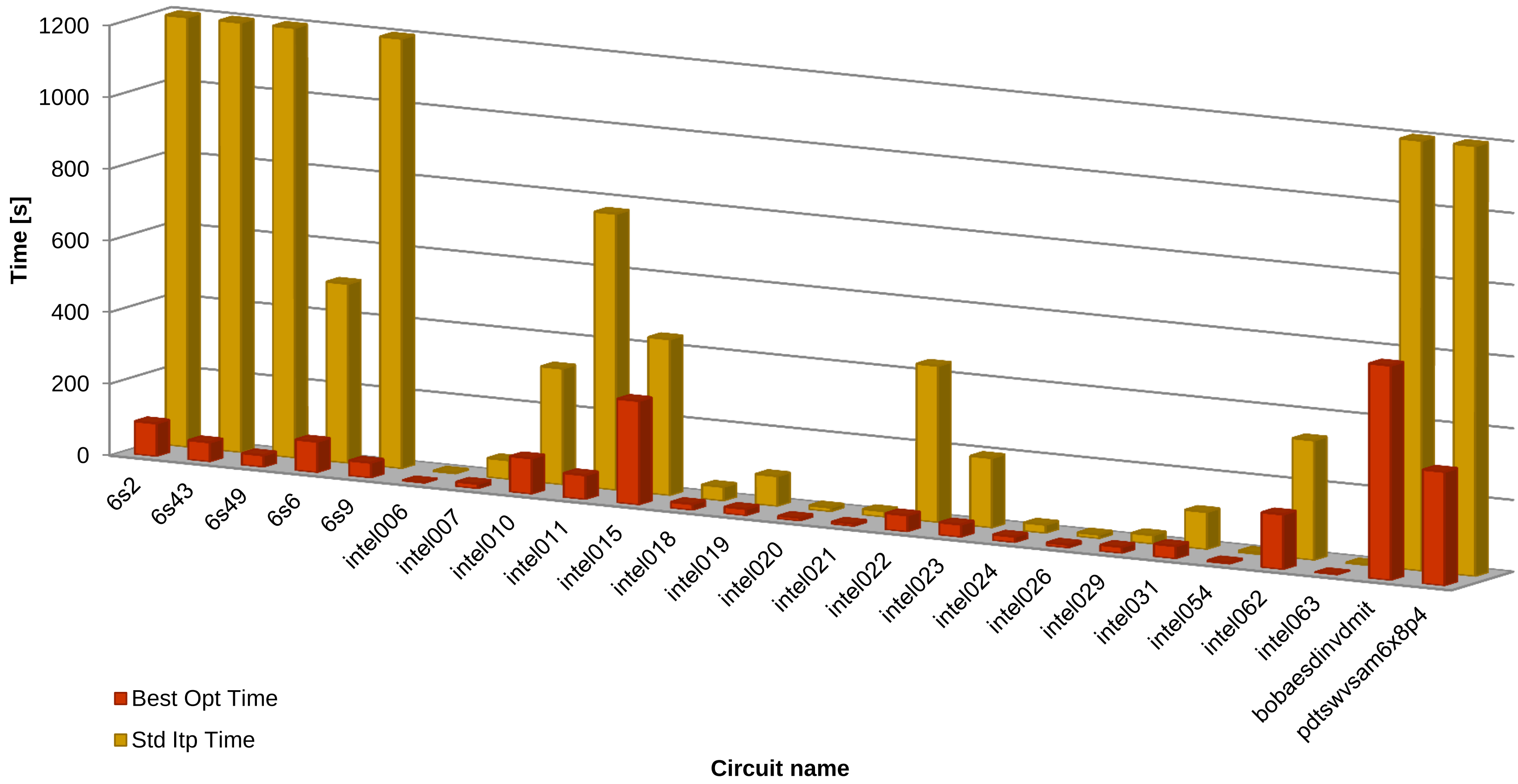
ITP = ITE(N_i,ITP_1,ITP_0)

while max try reached

Experimental results

- Framework: *PdTrav*
  - State-of-the-art academic Model Checker
  - HWMCC ’07 to ‘12
    - Ranked 1st at 2010 Model Checking Competition – UNSAT category
- ITP compaction => better MC runs
- Experience on IBM & Intel benchmarks

Experimental results



Conclusions

- ITP-based MC heavily relies on scalability, i.e. ability to compact ITPs
- We developed effective techniques to compact ITPs.
  - *Scalable techniques, applied incrementally*
- Best suited as a second engine
  - Hard-to-prove properties (hard for IC3)
  - Explosion of standard interpolation
  - Can afford extra time (for memory)

Thank you!