Introduction to Logic
Propositional Logic

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Bad News

Stanford Did Not Make the Top 20!

UNIVERSITY	PARTY-SCHOOL RANK
Indiana University of Pennsylvania - Main Campus	1
Texas Christian University	2
Birmingham-Southern College	3
James Madison University	4
Tarleton State University	5
Savannah State University	6
Tulane University	7
Washington & Lee University	8
University of Dayton	9
Alcorn State University	10
University of California - Santa Barbara	11
North Carolina A & T State University	12
Colgate University	13
Florida Agricultural and Mechanical University	14
Prairie View A & M University	15
University of Georgia	16
Augustana College	17
The Ohio State University - Main Campus	18
Jackson State University	19
The University of Kansas	20

Source: WSJ/College Pulse 2024 Best Colleges in the U.S. ranking

- Wall Street Journal 27 September 2023.

Multiple Logics

→ Propositional Logic (logical operators)

*If **raining** and **cold**, then **wet**.*

Relational Logic (variables and quantifiers)

*If **abby** likes **x**, then **bess** likes **x**.*

Functional Logic (functional terms)

*{**a**, **b**} is a subset of {**a**, **b**, **c**}.*

Example

If Mary loves Pat, then Mary loves Quincy. If it is Monday, then Mary loves Pat or Mary loves Quincy.

If it is Monday, does Mary love Quincy?

If it is Monday, does Mary love Pat?

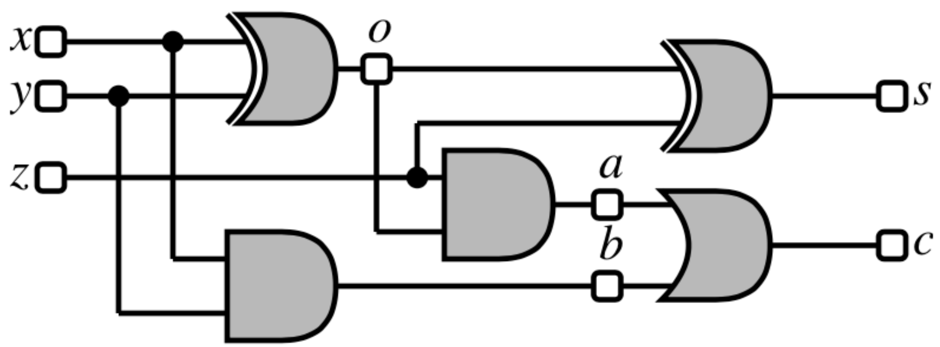
Example

Victor has been murdered, and Art, Bob, and Carl are suspects. Art says he did not do it. He says that Bob was the victim's friend but that Carl hated the victim. Bob says he was out of town the day of the murder, and besides he didn't even know the guy. Carl says he is innocent and he saw Art and Bob with the victim just before the murder. You can assume that everyone is telling the truth - except possibly for the murderer.

Whodunnit? (Answer: Bob)

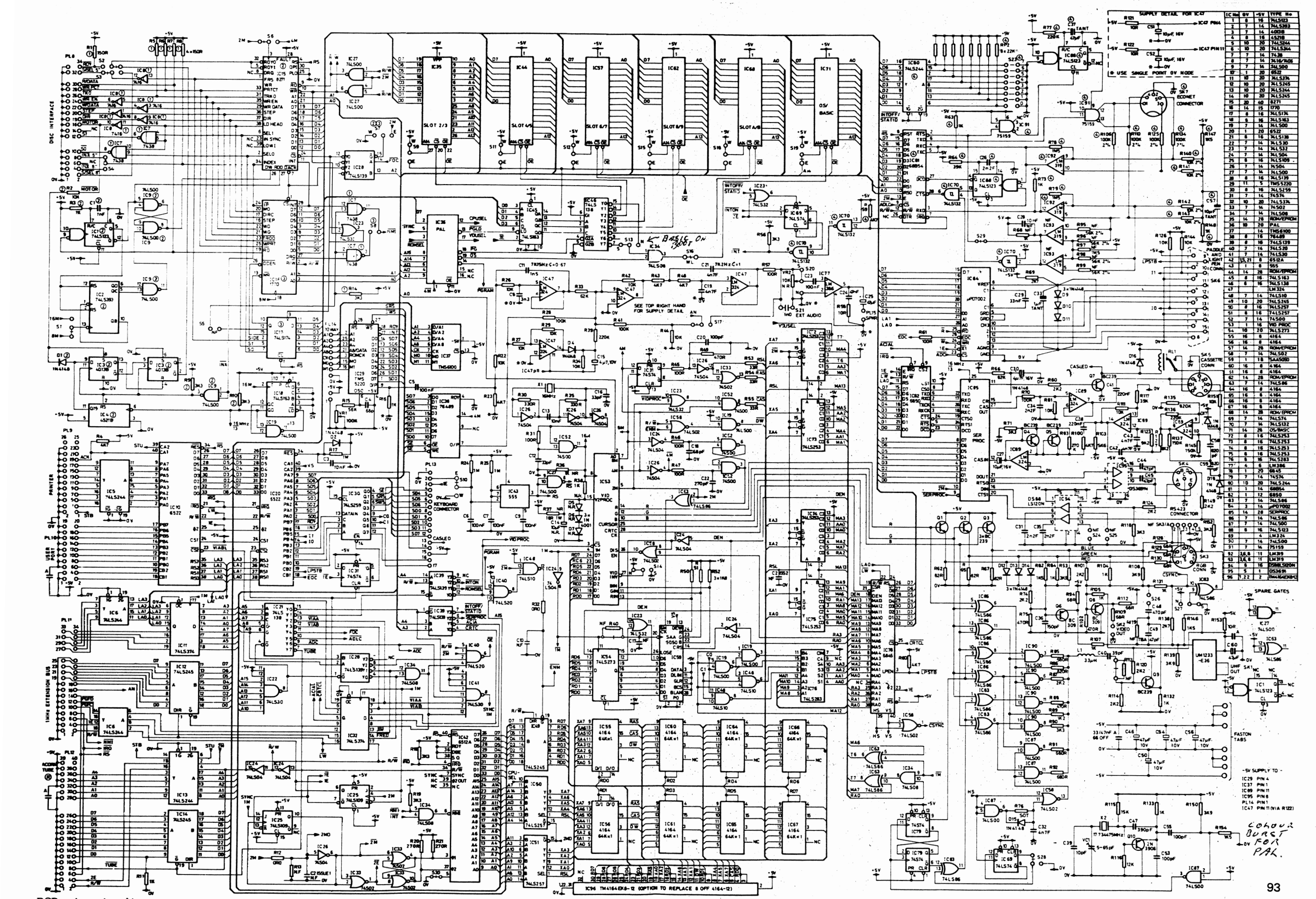
http://intrologic.stanford.edu/extras/whodunnit.html

Digital Circuits



http://intrologic.stanford.edu/extras/circuits.html

Digital Circuits Example



PCB circuit diagram

Natural Language

If Mary loves Pat, then Mary loves Quincy.

If it is Monday and raining, then Mary loves Pat or Quincy.

If it is Monday and raining, does Mary love Quincy?

Symbolic Logic

If Mary loves Pat, then Mary loves Quincy.

$$(p \Rightarrow q)$$

If it is Monday and raining, then Mary loves Pat or Quincy.

$$(m \wedge r \Rightarrow p \vee q)$$

If it is Monday and raining, does Mary love Quincy?

$$(m \wedge r \Rightarrow q)$$

Logical Sentences

Propositional Languages

A *propositional vocabulary* is a set/sequence of primitive symbols, called *proposition constants*.

Given a propositional vocabulary, a *propositional sentence* is either

(1) a member of the vocabulary or
(2) a compound expression using logical operators.

A *propositional language* is the set of *all* propositional sentences that can be formed from a propositional vocabulary.

Proposition Constants

By convention (in this course), proposition constants are written as strings of alphanumeric characters beginning with a lower case letter.

Examples:

raining
r32aining
rAiNiNg
rainingorsnowing

Non-Examples:

324567
raining.or.snowing

Compound Sentences (part I)

Negations:

$$\neg raining$$

The argument of a negation is called the *target*.

Conjunctions:

$$(raining \wedge snowing)$$

The arguments of a conjunction are called *conjuncts*.

Disjunctions:

$$(raining \vee snowing)$$

The arguments of a disjunction are called *disjuncts*.

Compound Sentences (part II)

Implications:

$$(raining \Rightarrow cloudy)$$

The left argument of an implication is the *antecedent*.
The right argument is the *consequent*.

Biconditionals:

$$(cloudy \Leftrightarrow raining)$$

Nested Compound Sentences

$\neg raining$

$(raining \wedge snowing)$

$(raining \vee snowing)$

$(raining \Rightarrow cloudy)$

$(cloudy \Leftrightarrow raining)$

$\neg(raining \wedge snowing)$

$((raining \wedge snowing) \Rightarrow cloudy)$

$(cloudy \Rightarrow (raining \wedge snowing))$

$((cloudy \wedge wet) \Leftrightarrow (raining \vee snowing))$

$(\neg raining \Rightarrow (cloudy \Rightarrow snowing))$

Parentheses Removal

Dropping Parentheses is good:

$$(p \wedge q) \rightarrow p \wedge q$$

But it can lead to ambiguities:

$$((p \vee q) \wedge r) \rightarrow p \vee q \wedge r$$

$$(p \vee (q \wedge r)) \rightarrow p \vee q \wedge r$$

Precedence

Parentheses can be dropped when the structure of an expression can be determined by precedence.

$$\neg$$
$$\wedge$$
$$\vee$$
$$\Rightarrow$$
$$\Leftrightarrow$$

An operand surrounded by operators associates with operator of higher precedence.

$$\neg p \vee q \rightarrow ((\neg p) \vee q)$$
$$p \vee q \wedge r \rightarrow (p \vee (q \wedge r))$$
$$p \wedge q \Rightarrow r \rightarrow ((p \wedge q) \Rightarrow r)$$
$$p \Rightarrow q \Leftrightarrow r \rightarrow ((p \Rightarrow q) \Leftrightarrow r)$$

Precedence

Parentheses can be dropped when the structure of an expression can be determined by precedence.

$$\neg$$
$$\wedge$$
$$\vee$$
$$\Rightarrow$$
$$\Leftrightarrow$$

An operand surrounded by operators associates with operator of higher precedence.

$$\neg p \vee q \rightarrow ((\neg p) \vee q)$$
$$p \vee q \wedge r \rightarrow (p \vee (q \wedge r))$$
$$p \wedge q \Rightarrow r \rightarrow ((p \wedge q) \Rightarrow r)$$
$$p \Rightarrow q \Leftrightarrow r \rightarrow ((p \Rightarrow q) \Leftrightarrow r)$$

Precedence (continued)

If surrounded by two occurrences of ∧ or ∨, the operand associates with the operator to the left.

$$p \wedge q \wedge r \rightarrow ((p \wedge q) \wedge r)$$
$$p \vee q \vee r \rightarrow ((p \vee q) \vee r)$$

If surrounded by two occurrences of ⇒ or ⇔, the operand associates with the operator to the right.

$$p \Rightarrow q \Rightarrow r \rightarrow (p \Rightarrow (q \Rightarrow r))$$
$$p \Leftrightarrow q \Leftrightarrow r \rightarrow (p \Leftrightarrow (q \Leftrightarrow r))$$

Semantics

Propositional Interpretation

A *propositional interpretation* is an association between the propositional constants in a propositional language and the values T or F.

$$p \xrightarrow{i} \mathrm{T} \qquad p^i = \mathrm{T}$$

$$q \xrightarrow{i} \mathrm{F} \qquad q^i = \mathrm{F}$$

$$r \xrightarrow{i} \mathrm{T} \qquad r^i = \mathrm{T}$$

We sometimes write 1 and 0 in place of T and F.

$$p^i = 1$$

$$q^i = 0$$

$$r^i = 1$$

Sentential Interpretation

A *sentential interpretation* is an association between the sentences in a propositional language and the truth values T or F.

$p^i = \mathrm{T}$	$(p \vee q)^i = \mathrm{T}$
$q^i = \mathrm{F}$	$(\neg q \vee r)^i = \mathrm{T}$
$r^i = \mathrm{T}$	$((p \vee q) \wedge (\neg q \vee r))^i = \mathrm{T}$

NB: Each distinct propositional interpretation gives rise to a unique sentential interpretation due to operator semantics.

Semantics of Negations

A *negation* is true if and only if the target is false.

ϕ	$\neg\phi$
T	F
F	T

For example, if the interpretation of p is F, then the interpretation of $\neg p$ is T.

For example, if the interpretation of $(p \wedge q)$ is T, then the interpretation of $\neg(p \wedge q)$ is F.

Semantics of Conjunctions

A *conjunction* is true if and only if both conjuncts are true.

ϕ	ψ	$\phi \wedge \psi$
T	T	T
T	F	F
F	T	F
F	F	F

For example, if the interpretation of p is true and q is true, then $(p \wedge q)$ is true.

Semantics of Disjunctions

A *disjunction* is true if and only if at least one of the disjuncts is true.

ϕ	ψ	$\phi \vee \psi$
T	T	T
T	F	T
F	T	T
F	F	F

The type of disjunction here is called *inclusive or*. This contrasts with *exclusive or*, which says that a disjunction is true if and only if an *odd number* of disjuncts are true.

Semantics of Biconditionals

A *biconditional* is true if and only if the truth values of its two constituents are the same.

ϕ	ψ	$\phi \Leftrightarrow \psi$
T	T	T
T	F	F
F	T	F
F	F	T

Semantics of Implications

An *implication* is true if and only if the antecedent is false or the consequent is true.

ϕ	ψ	$\phi \Rightarrow \psi$
T	T	T
T	F	F
F	T	T
F	F	T

The semantics of implication here is called *material implication*.

Implications and Biconditionals

ϕ	ψ	$\phi \Rightarrow \psi$
T	T	T
T	F	F
F	T	T
F	F	T

ϕ	ψ	$\psi \Rightarrow \varphi$
T	T	T
T	F	T
F	T	F
F	F	T

ϕ	ψ	$\phi \Leftrightarrow \psi$
T	T	T
T	F	F
F	T	F
F	F	T

$\varphi \Leftrightarrow \psi$ is true if and only if $\varphi \Rightarrow \psi$ and $\psi \Rightarrow \varphi$ are true.

Counterfactuals are Weird

An *implication* is true if and only if the antecedent is false or the consequent is true.

ϕ	ψ	$\phi \Rightarrow \psi$
T	T	T
T	F	F
F	T	T
F	F	T

A counterfactual is an implication in which the antecedent is false. NB: Counterfactuals are always *true!*

$$\textit{Shakespeare is alive} \Rightarrow \textit{Shakespeare is dead}$$

$$2+2=5 \Rightarrow 2+2=7$$

Evaluation

Evaluation

Interpretation i:

$$p^i = \text{T}$$
$$q^i = \text{T}$$
$$r^i = \text{F}$$

Compound Sentence

$$(p \vee q) \wedge (\neg q \vee r)$$
$$(\text{T} \vee \text{T}) \wedge (\neg \text{T} \vee \text{F})$$
$$(\text{T} \vee \text{T}) \wedge (\ \text{F} \ \vee \text{F})$$
$$\text{T} \quad \wedge \quad \text{F}$$
$$\text{F}$$

Evaluation

Interpretation i:

$$p^i = T$$
$$q^i = F$$
$$r^i = T$$

Compound Sentence

$$(p \vee q) \wedge (\neg q \vee r)$$
$$(T \vee F) \wedge (\neg F \vee T)$$
$$(T \vee F) \wedge (T \vee T)$$
$$T \quad \wedge \quad T$$
$$T$$

Evaluation

Interpretation i:

$$p^i = \mathrm{T}$$
$$q^i = \mathrm{F}$$
$$r^i = \mathrm{T}$$

Compound Sentence

$$(p \land q) \lor (\neg q \land r)$$
$$(\mathrm{T} \land \mathrm{F}) \lor (\neg \mathrm{F} \land \mathrm{T})$$
$$(\mathrm{T} \land \mathrm{F}) \lor (\mathrm{T} \land \mathrm{T})$$
$$\mathrm{F} \quad \lor \quad \mathrm{T}$$
$$\mathrm{T}$$

Satisfaction

Evaluation versus Satisfaction

Evaluation:

$$\begin{array}{lcl} p^i & = & \mathrm{T} \\ q^i & = & \mathrm{F} \end{array} \longrightarrow \begin{array}{lcl} (p \vee q)^i & = & \mathrm{T} \\ (\neg q)^i & = & \mathrm{T} \end{array}$$

Satisfaction:

$$\begin{array}{lcl} (p \vee q)^i & = & \mathrm{T} \\ (\neg q)^i & = & \mathrm{T} \end{array} \longrightarrow \begin{array}{lcl} p^i & = & \mathrm{T} \\ q^i & = & \mathrm{F} \end{array}$$

Multiple Interpretations

Logic does not prescribe which interpretation is "correct". In the absence of additional information, one interpretation is as good as another.

Interpretation i

$$p^i = T$$
$$q^i = F$$
$$r^i = T$$

Interpretation j

$$p^j = F$$
$$q^j = F$$
$$r^j = T$$

Examples:

- Different days of the week
- Different locations
- Beliefs of different people

Truth Tables

A *truth table* is a table of all possible interpretations for the propositional constants in a language.

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

One column per constant.

One row per interpretation.

For a language with n constants, there are 2^n interpretations.

Truth Table Method

Method to find all propositional interpretations that satisfy a given set of sentences:

(1) Form a truth table for the propositional constants.

(2) For each sentence in the set and each row in the truth table, check whether the row satisfies the sentence. If not, cross out the row.

(3) Any row remaining satisfies all sentences in the set. (Note that there might be more than one.)

Are these sentences satisfiable?

$$q \Rightarrow r$$

$$p \Rightarrow q \wedge r$$

$$\neg r$$

Satisfaction Example

$$p \Rightarrow q \wedge r$$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

Satisfaction Example

$q \Rightarrow r$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

$p \Rightarrow q \wedge r$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

Satisfaction Example

$q \Rightarrow r$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

$p \Rightarrow q \wedge r$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

$\neg r$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

Satisfaction Example

$$\{q \Rightarrow r,\ p \Rightarrow q \wedge r,\ \neg r\}$$

p	q	r
T	T	T
T	T	F
T	F	T
T	F	F
F	T	T
F	T	F
F	F	T
F	F	F

Logica

Course Website

http://logica.stanford.edu

Logica

Babbage
Truth Tables

Boole
Multicolumn Truth Tables

Clarke
Logic Grids

Quine
Equivalence Editor

Stickel
Clausal Form Converter

Wegman
Unifier

Hilbert
Hilbert-style Proof Editor

Fitch
Fitch-style Proof Editor

Robinson
Resolution Proof Editor

Wos
Resolution + Paramodulation

Babbage

Show Instructions

Premises:

```
q=>r
p => q&r
~r
```

Truth Table

Constants			Premises		
q	**r**	**p**	**q => r**	**p => q & r**	**~r**
1	1	1	1	1	0
1	1	0	1	1	0
1	0	1	0	0	1
1	0	0	0	1	1
0	1	1	1	0	0
0	1	0	1	1	0
0	0	1	1	0	1
0	0	0	1	1	1

Interleaved Generation and Checking

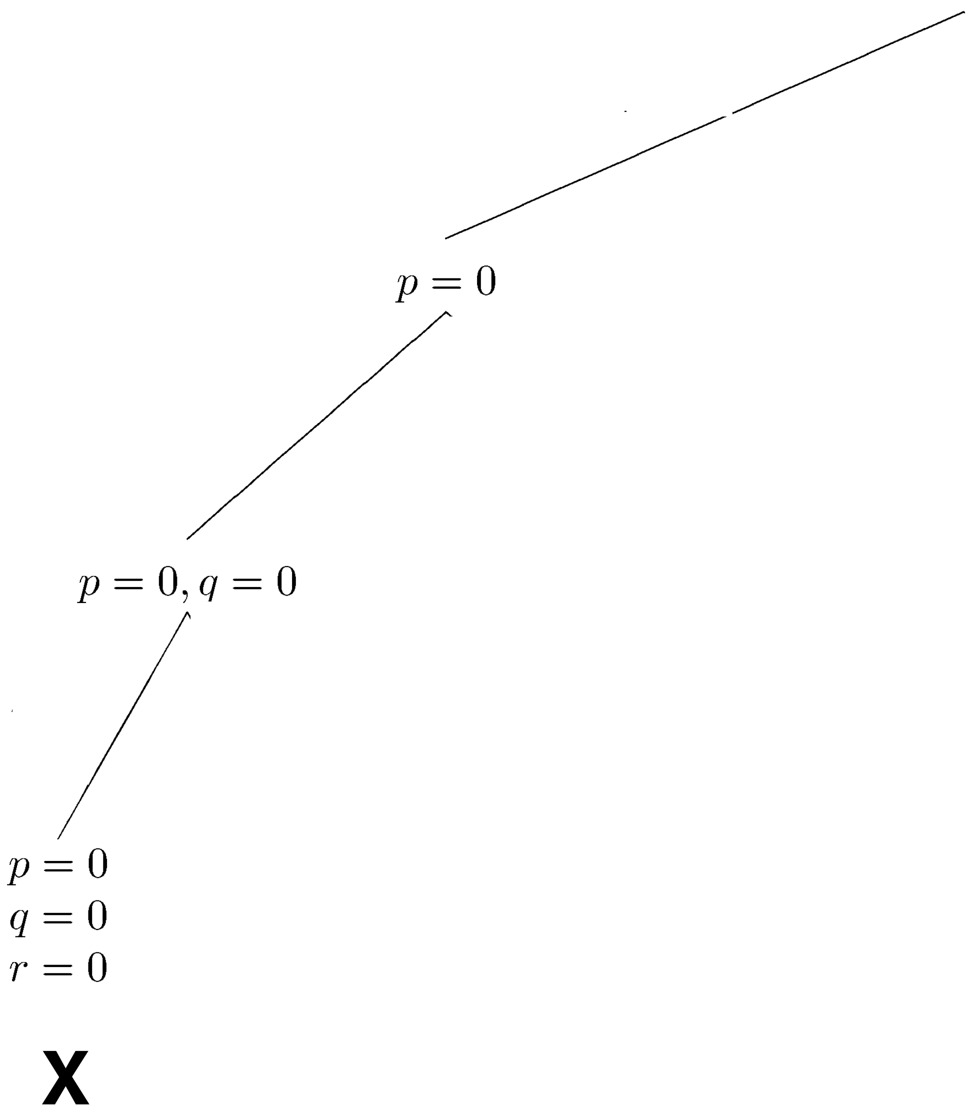
Generation then Evaluation

$$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$$

p	q	r	$p \vee q$	$p \vee \neg q$	$\neg p \vee q$	$\neg p \vee \neg q \vee \neg r$	$\neg p \vee r$	Δ
0	0	0	0	1	1	1	0	0
0	0	1	0	1	1	1	1	0
0	1	0	1	0	1	1	1	0
0	1	1	1	0	1	1	1	0
1	0	0	1	1	0	1	0	0
1	0	1	1	1	0	1	1	0
1	1	0	1	1	1	1	0	0
1	1	1	1	1	1	0	1	0

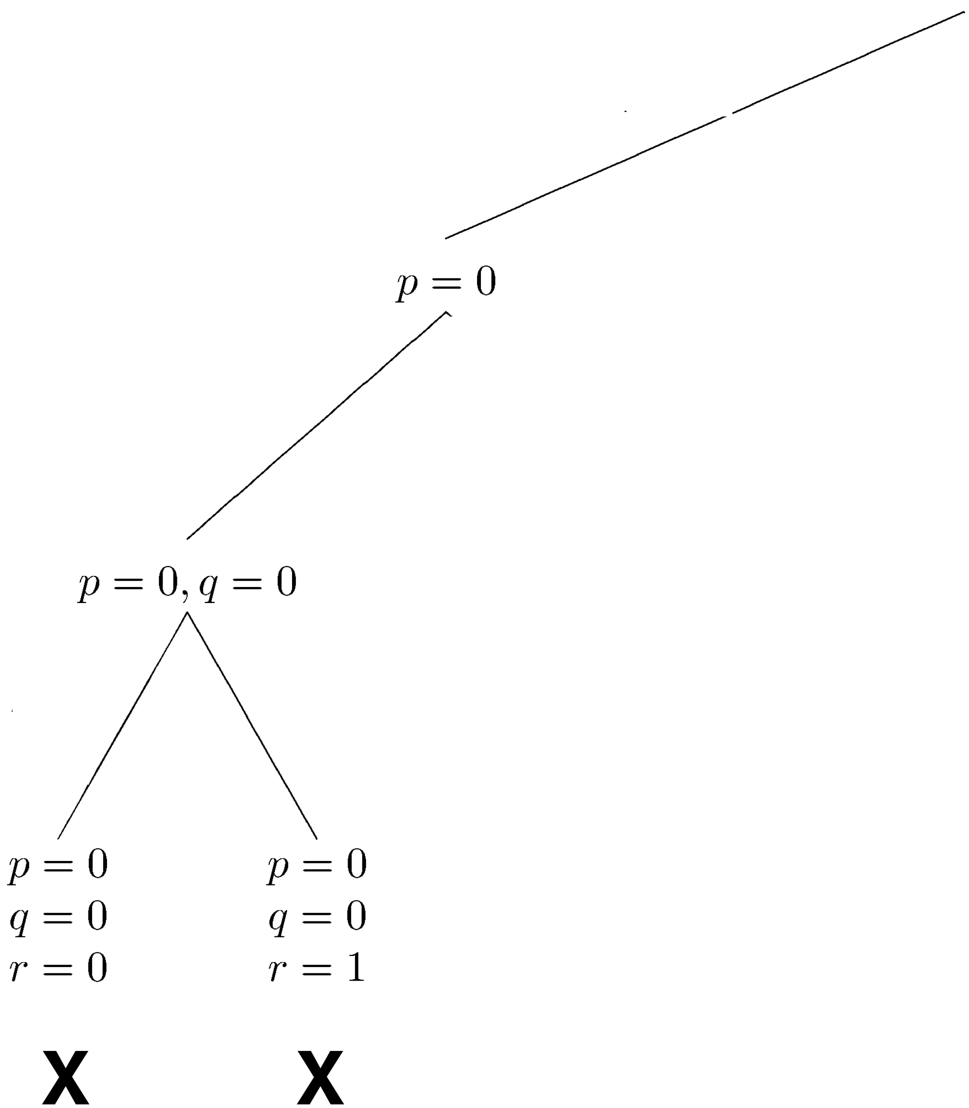
Interleaved Generation and Evaluation

$$\{p \lor q,\ p \lor \neg q,\ \neg p \lor q,\ \neg p \lor \neg q \lor \neg r,\ \neg p \lor r\}$$



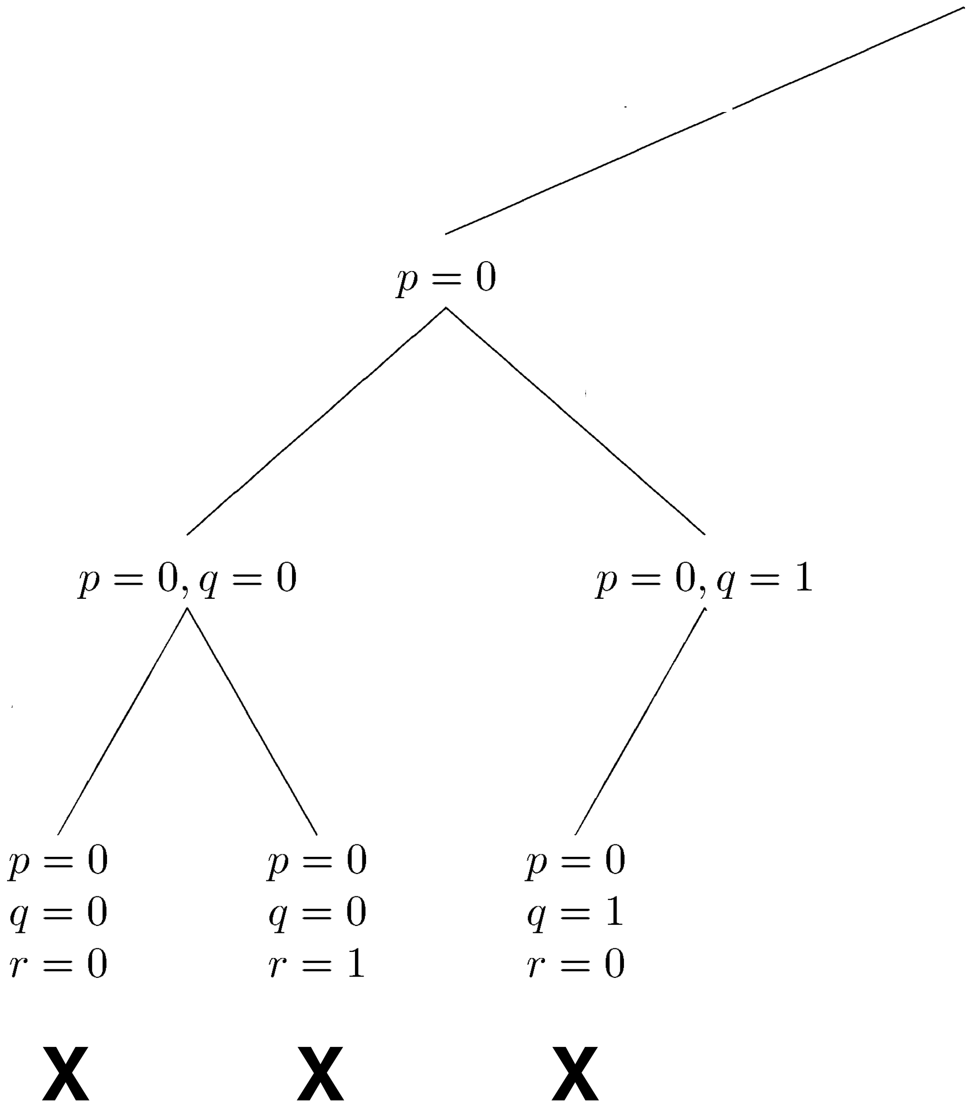
Interleaved Generation and Evaluation

$$\{p \lor q,\ p \lor \neg q,\ \neg p \lor q,\ \neg p \lor \neg q \lor \neg r,\ \neg p \lor r\}$$



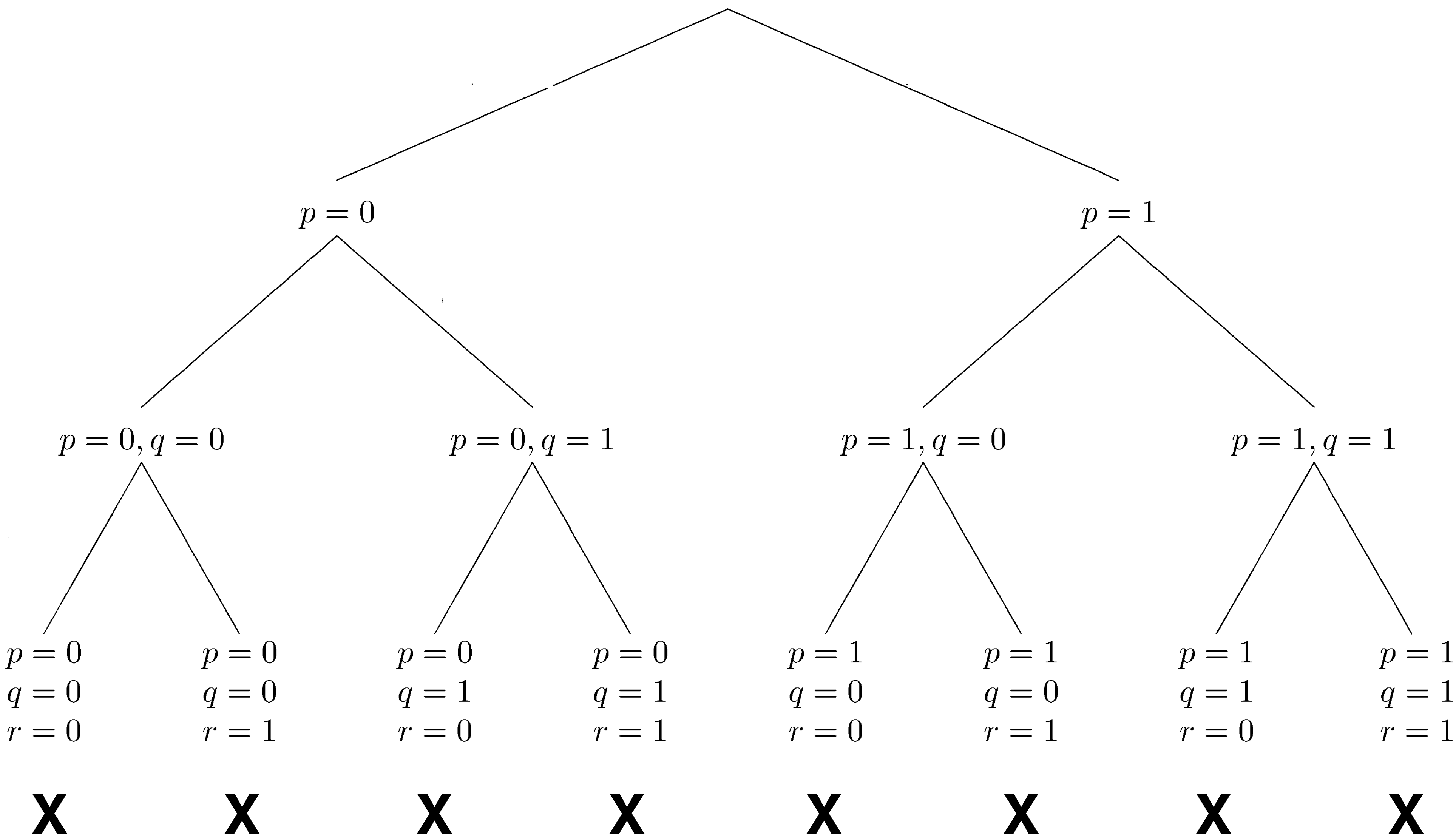
Interleaved Generation and Evaluation

$$\{p \lor q,\ p \lor \neg q,\ \neg p \lor q,\ \neg p \lor \neg q \lor \neg r,\ \neg p \lor r\}$$



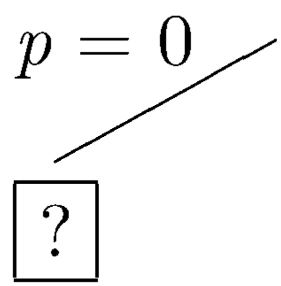
Interleaved Generation and Evaluation

$$\{p \lor q,\ p \lor \neg q,\ \neg p \lor q,\ \neg p \lor \neg q \lor \neg r,\ \neg p \lor r\}$$



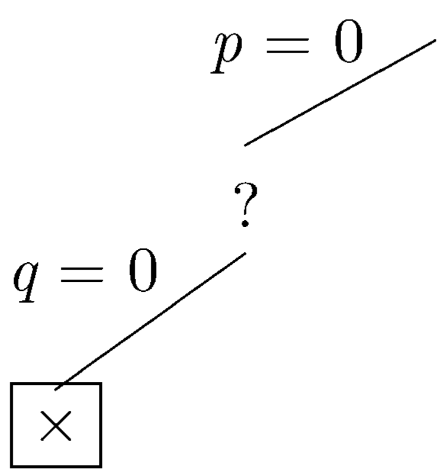
Intermediate State Checking

$$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$$



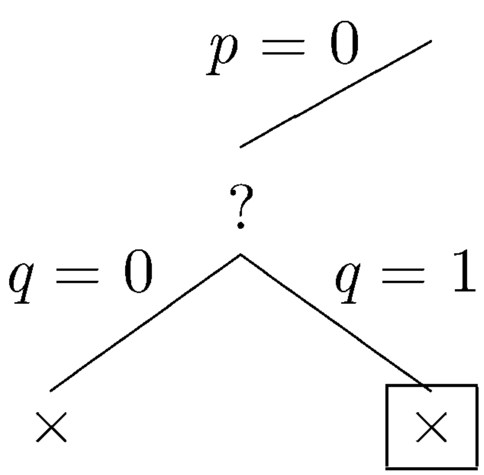
Intermediate State Checking

$$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$$



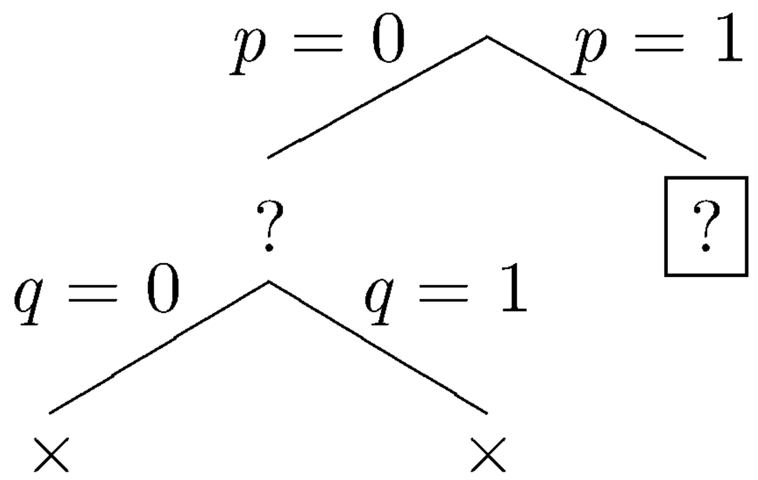
Intermediate State Checking

$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$



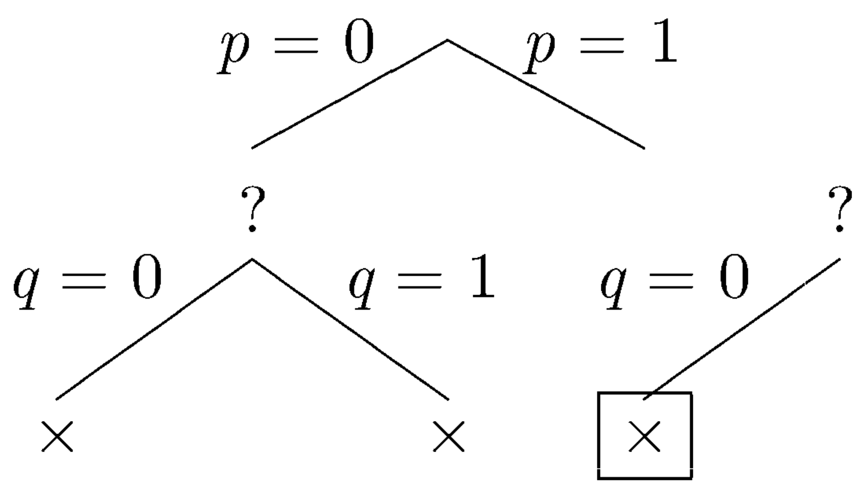
Intermediate State Checking

$$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$$



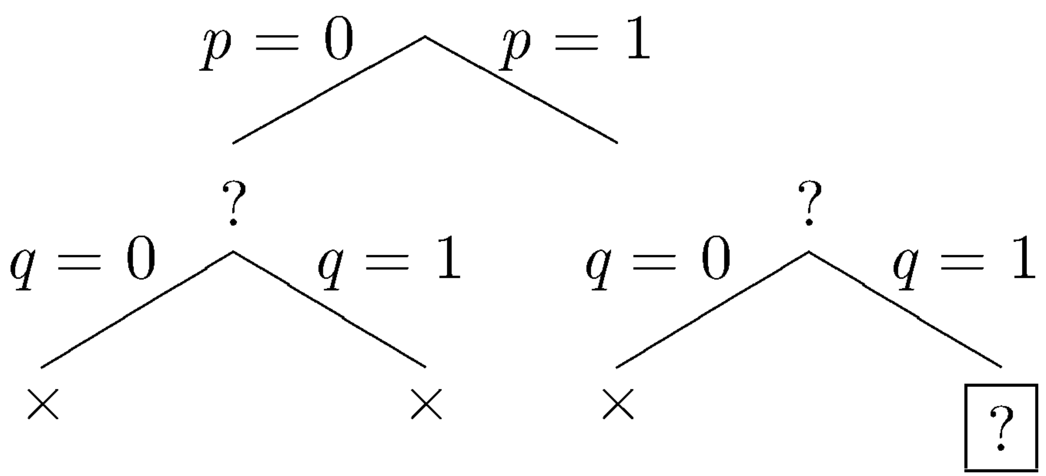
Intermediate State Checking

$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$



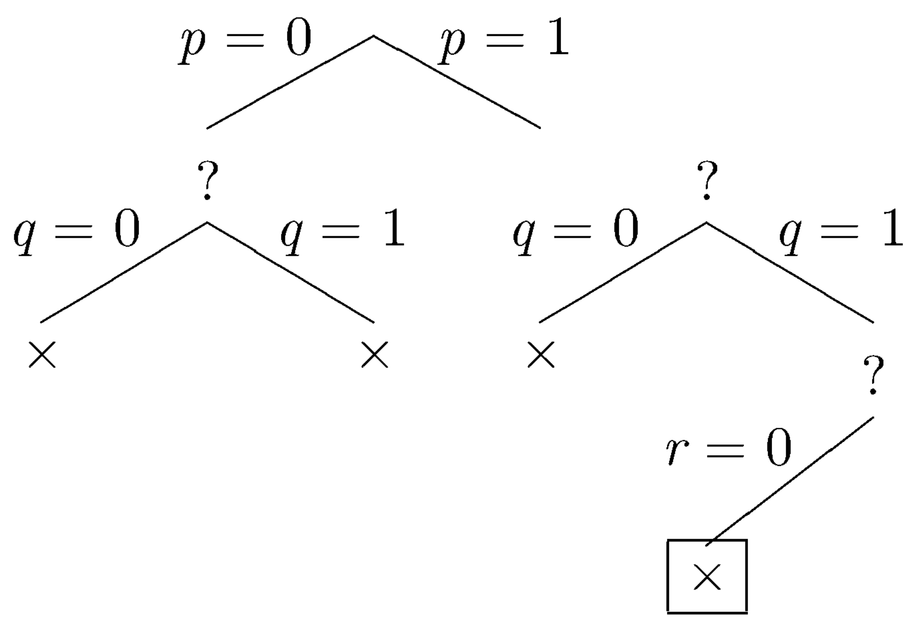
Intermediate State Checking

$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$



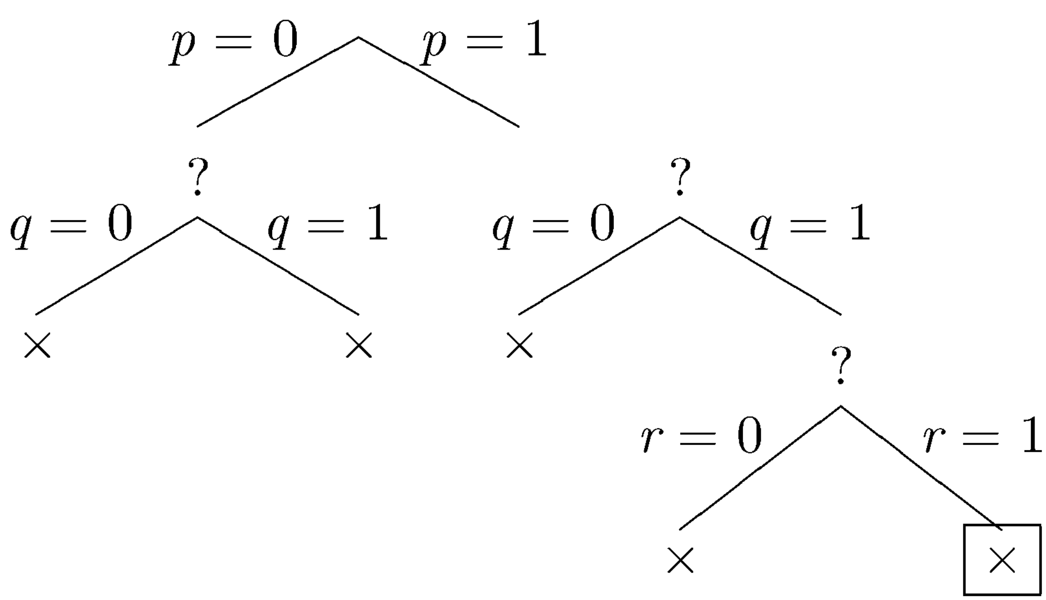
Intermediate Checking

$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$



Intermediate Checking

$$\{p \vee q,\ p \vee \neg q,\ \neg p \vee q,\ \neg p \vee \neg q \vee \neg r,\ \neg p \vee r\}$$



Simplification and Unit Propagation

Simplification

Constraints

$p \vee q$

$p \vee \sim q$

$\sim p \vee q$

$\sim p \vee \sim q \vee \sim r$

$\sim p \vee r$

Simplification

Given $p = 1$

Original	**Simplified**
$p \lor q$	-
$p \lor \sim q$	-
$\sim p \lor q$	q
$\sim p \lor \sim q \lor \sim r$	$\sim q \lor \sim r$
$\sim p \lor r$	r

Unit Propagation

Given $p = 1, q = 1$

Original	**Simplified**
$p \vee q$	-
$p \vee \sim q$	-
$\sim p \vee q$	-
$\sim p \vee \sim q \vee \sim r$	$\sim r$
$\sim p \vee r$	r

Simplification

Given $p = 1, q = 1, r = 1$

Original	**Simplified**
$p \vee q$	-
$p \vee \sim q$	-
$\sim p \vee q$	-
$\sim p \vee \sim q \vee \sim r$	X
$\sim p \vee r$	-

More on Computing Satisfaction

http://intrologic.stanford.edu/extras/satisfiability.html

Word of the Day

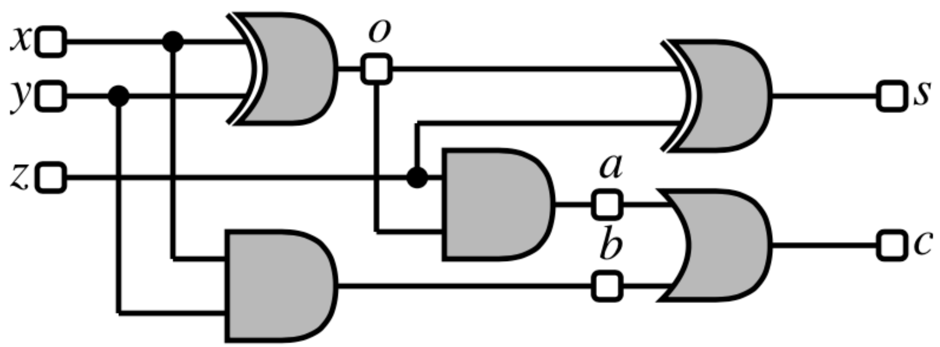
Counterfactual

Word of the Day

Counterfactual

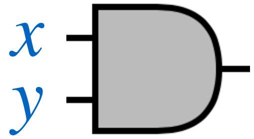
Digital Circuits

Digital Circuits

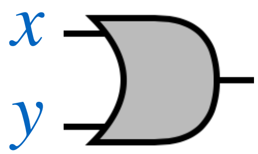


http://intrologic.stanford.edu/extras/circuits.html

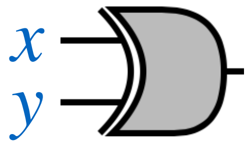
Gates



$x \wedge y$



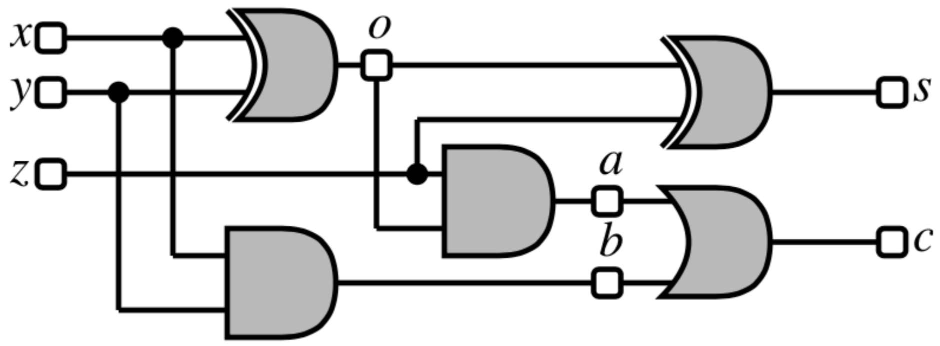
$x \vee y$



$(x \wedge \neg y) \vee (\neg x \wedge y)$

$\neg(x \Leftrightarrow y)$

Example



o: $(x \wedge \neg y) \vee (\neg x \wedge y)$

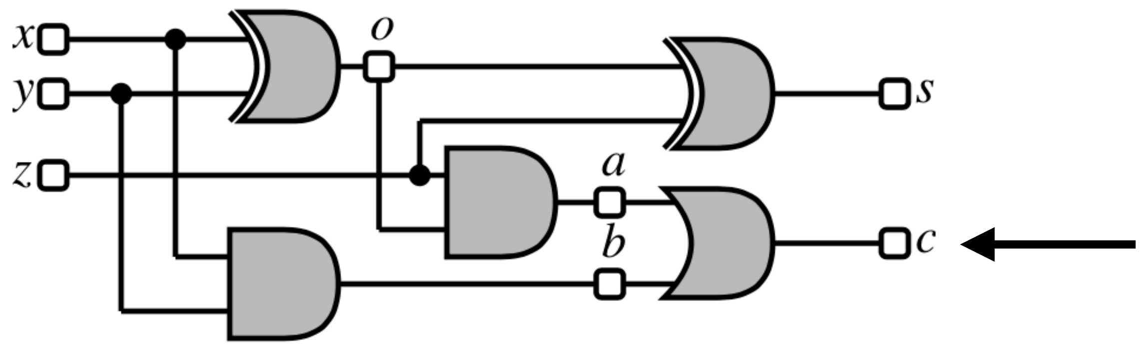
b: $x \wedge y$

a: $z \wedge ((x \wedge \neg y) \vee (\neg x \wedge y))$

c: $(z \wedge ((x \wedge \neg y) \vee (\neg x \wedge y))) \vee (x \wedge y)$

Evaluation Example

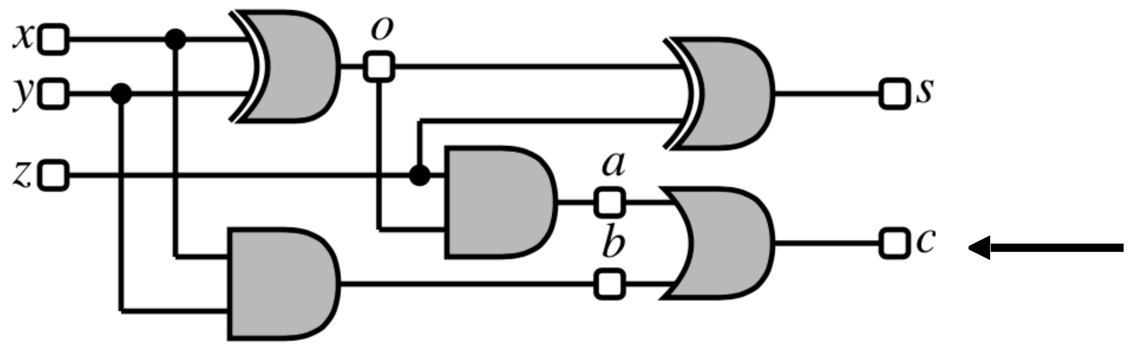
$x^i = \mathrm{T}$
$y^i = \mathrm{F}$
$z^i = \mathrm{T}$



$$[(z \wedge ((x \wedge \neg y) \vee (\neg x \wedge y))) \vee (x \wedge y)]^i = ?$$

Example

x^i = T
y^i = F
z^i = T



$$(z \wedge ((x \wedge \neg y) \vee (\neg x \wedge y))) \vee (x \wedge y)$$

(T ∧ ((T ∧ ¬F) ∨ (¬T ∧ F))) ∨ (T ∧ F)

(T ∧ ((T ∧ T) ∨ (F ∧ T))) ∨ (T ∧ F)

(T ∧ (T ∨ F)) ∨ F

(T ∧ T) ∨ F

T ∨ F

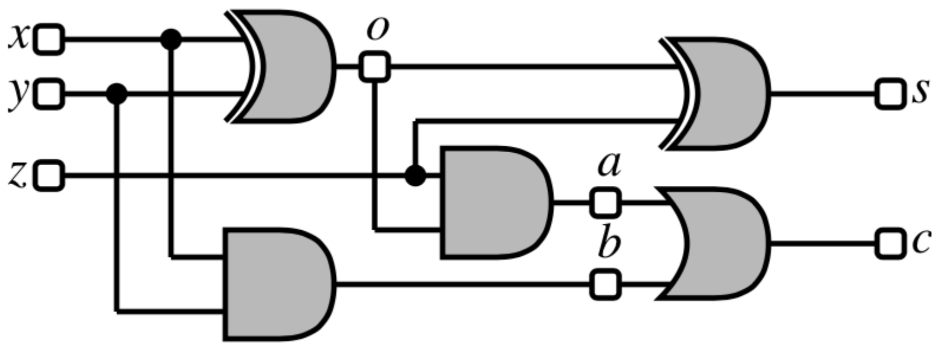
T

Satisfaction Example

$x^i = ?$

$y^i = ?$

$z^i = ?$



$$((z \wedge ((x \wedge \neg y) \vee (\neg x \wedge y))) \vee (x \wedge y))^i = \mathrm{T}$$

Constants			Premises
z	x	y	z & (x & ~y | ~x & y) | x & y
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	0
0	1	1	1
0	1	0	0
0	0	1	0
0	0	0	0

Digital Circuits Extras

Evaluation, Satisfaction, Diagnosis, Testing

http://intrologic.stanford.edu/extras/circuits.html

Graphical design and simulation

https://logic.ly/demo/

The Big Game

The Big Game

Stanford people always tell the truth, and Berkeley people always lie. Unfortunately, by looking at a person, you cannot tell whether he is from Stanford or Berkeley.

You come to a fork in the road and want to get to the football stadium down one fork. However, you do not know which to take. There is a person standing there. What single question can you ask him to help you decide which fork to take?

Basic Idea

left	*su*	*Question*	*Response*
T	T		
T	F		
F	T		
F	F		

Desired Response

left	*su*	*Question*	*Response*
T	T		"T"
T	F		"T"
F	T		"F"
F	F		"F"

Desired Response

left	*su*	*Question*	*Response*
T	T	T	"T"
T	F	F	"T"
F	T	F	"F"
F	F	T	"F"

The Big Game (solved)

Question: *The left road is the way to the stadium if and only if you are from Stanford. Is that correct?*

$$left \Leftrightarrow su$$

Let's Be Careful Out There