# Complexity Theory
# Complexity

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# Graph Coloring

- Instance: A graph **G = (V, E)** and an integer **k**.
- Question: Can **G** be "properly colored" with at most **k** colors?
- Proper Coloring: one of the **k** colors is assigned to each vertex so that adjacent vertices have different colors.
- Suppose we have two instances of this problem (1) is True (Yes) and the other (2) is False (No).
- AND you know (1) is Yes and (2) is No. (Maybe you have a secret program that has analyzed the two instance.)

# Checking a “Yes” Answer

- Without showing how your program works (you may not even know), how can you convince someone else that instance (1) is, in fact, a Yes instance?
- We can assume the output of the program was an actual coloring of **G**. Just give that to a doubter who can easily check that no adjacent vertices are colored the same, and that no more than **k** colors were used.
- How about the No instance?
- What could the program have given that allows us to quickly "verify" (2) is a No instance?
  - No One Knows!!
- <u>For all</u> problems seem to be harder than <u>there exists</u> ones in many contexts
- Think re versus co-re

# Checking a “No” Answer

- The only thing anyone has thought of is to have it test all possible ways to **k**-color the graph – all of which fail, of course, if “No” is the correct answer.
- There are an exponential number of things (colorings) to check.
- For some problems, there seems to be a big difference between verifying Yes and No instances.
- To solve a problem efficiently, we must be able to solve both Yes and No instances efficiently and so it would seem we should be able to verify both quickly.


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# Hard and Easy

- True Conjecture: If a problem is easy to solve, then it is easy to verify (just solve it and compare).
- Contrapositive: If a problem is hard to verify, then it is (probably) hard to solve.
- There is nothing magical about Yes and No instances – sometimes the Yes instances are hard to verify and No instances are easy to verify.
- And, of course, sometimes both are hard to verify.

# Easy Verification

- Are there problems in which both Yes and No instances are easy to verify?

- Yes. For example: Search a list **L** of **n** values for a key **x**.
- Question: Is **x** in the list **L**?

- Yes and No instances are both easy to verify.

- In fact, the entire problem is easy to solve!!
- Analogy: recursive means re and co-re

# Verify vs Solve

- **Conjecture**: If both Yes and No instances are easy to verify, then the problem is easy to solve.
- **Analogy** (**Failure**?): Does re/co-re imply recursive have analogy here?

- No one has yet proven this claim, but most researchers believe it to be true.
- Note: It is usually relatively easy to prove something is easy – just write an algorithm for it and prove it is correct and that it is fast (usually, we mean polynomial).
- But it is usually very difficult to prove something is hard – we may not be clever enough yet. So, you will often see "appears to be hard."


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# A CS Grand Challenge

**Does *P*=*NP*?**

There are many equivalent ways to describe *P* and *NP*. For now, we will use the following.

***P*** is the set of decision problems (those whose instances have "Yes"/ "No" answers) that can be solved in polynomial time on a deterministic computer (no concurrency or guesses allowed).

***NP*** is the set of decision problems that can be solved in polynomial time on a non-deterministic computer (equivalently one that can spawn an unbounded number of parallel threads; equivalently one that can be verified in polynomial time on a deterministic computer).

Again, as "Does ***P*=*NP*?**" has just one question, it is **solvable**, we just don't yet know which solution, "Yes" or "No", is the correct one.


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# Decision vs Optimization

Two types of problems are of particular interest:

Decision Problems ("Yes/No" answers)

Optimization problems ("best" answers)

(there are other types)


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# Vertex Cover (VC)

- Suppose we are in charge of a large network (a graph where edges are links between pairs of cities (vertices). Periodically, a line fails. To mend the line, we must call in a repair crew that goes over the line to fix it. To minimize down time, we station a repair crew at one end of every line. How many crews must you have and where should they be stationed?
- This is called the Vertex Cover Problem. (Yes, it sounds like it should be called the Edge Cover problem – something else already had that name.)
- An interesting problem – it seems to a hard problems but may not be.

# VC Decision vs Optimization

- As a Decision Problem:
  - Instances: A graph **G** and an integer **k**.
  - Question: Does **G** possess a vertex Cover with at most **k** vertices?
- As an Optimization Problem:
  - Instances: A graph **G**.
  - Question: What is the smallest **k** for which **G** possesses a vertex cover?

# Relation of VC Problems

- If we can (easily) solve either one of these problems, we can (easily) solve the other. To solve the optimization version, just solve the decision version with several different values of **k**. Use a binary search on **k** between **1** and **n**. That is **log(n)** solutions of the decision problem solves the optimization problem. It's simple to solve the decision version if we can solve the optimization version.

- We say their time complexity differs by no more than a multiple of **log(n)**.
- If one is polynomial, then so is the other.
- If one is exponential, then so is the other.

- We say they are equally difficult (both poly. or both exponential).

# A Word about Time

An algorithm for a problem is said to be polynomial if there exists integers **k** and **N** such that **t(n)**, the maximum number of steps required on any instance of size **n**, is at most $\mathbf{n^k}$, for all $\mathbf{n \geq N}$.

Otherwise, we say the algorithm is exponential. Usually, this is interpreted to mean $\mathbf{t(n) \geq c^n}$ for an infinite set of size **n** instances, and some constant $\mathbf{c > 1}$ (often, we simply use $\mathbf{c = 2}$).


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# Three Classes of Problems

Problems proven to be in these three groups (classes) are, respectively,

Undecidable, Exponential, and Polynomial.

Theoretically, all problems belong to exactly one of these three classes.


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# Unknown Complexity

Practically, there are a lot of problems (maybe, most) that have not been proven to be in any of the classes (Yet, maybe never will be).

Most currently "lie between" polynomial and exponential – we know of exponential algorithms but have been unable to prove that exponential algorithms are necessary.

Some may have polynomial algorithms, but we have not yet been clever enough to discover them.


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# Subset Sum

- Problem – Subset Sum

- Instances: A list **L** of **n** integer values and an integer **B**.
- Question: Does **L** have a subset which sums exactly to **B**?

- No one knows of a polynomial (deterministic) solution to this problem.

- On the other hand, there is a very simple (dynamic programming) algorithm that runs in **O(nB)** time.

- Why isn't this "polynomial"?
  - Because the "length" of an instance is **nlog(B)** and
  - **nB > (nlog(B))^k** for any fixed **k**.


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# Research Territory

**Decidable – vs – Undecidable**
**(area of Computability Theory)**

**Exponential – vs – polynomial**
**(area of Computational Complexity)**

**Algorithms for any of these**
**(area of Algorithm Design/Analysis)**


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# NonDeterminism

# Models of Computation

## Non-Determinism

Since we can't seem to find a model of computation that is more powerful than a TM, can we find one that is 'faster'?

In particular, we want one that takes us from exponential time to polynomial time.

Our candidate will be the Non-Deterministic Turing Machine (NDTM).


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# NDTMs

As NDTMs are automata, we only care about what they accept and generally have just one accepting state. We want to determine how long it takes to get to the accept state - that's our only motive!!

So, what is a NDTM doing?

In a NDTM, like in a NFA or NPDA, what we are doing is making, and testing, all of those choices at once by 'spawning' a different NDTM for each of them. Those that don't work out, simply die (or something).

This is the ultimate in parallel programming.



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# NDTM and Oracles

Another interpretation of non-determinism:

From the basic definition, we notice that out of every state having a non-deterministic choice, at least one choice is valid and all the rest sort of die off. That is, they really have no reason for being spawned for this instance. So, we station at each such state, an 'oracle' (an all-knowing being) who only allows the correct NDTM to be spawned.

An 'Oracle Machine.'

All we care about is the time associated with the right choices. In fact, we can have a single oracle that makes all the right choices in advance, if they exist.

# Checking an Oracle/Witness

**For example, in the SubsetSum problem, we ask the oracle to write down the subset of objects whose sum is B (the desired sum). Then we ask "Can we write a deterministic polynomial algorithm to test the given witness."**

**The answer for SubsetSum is Yes, we can, i.e., the witness is verifiable in deterministic polynomial time.**

# NDTMs - Witnesses

Just what can we ask and expect of a "witness"?

The witness must be something that

(1) we can verify to be accurate (for the given problem and instance) and

(2) we must be able to "finish off" the solution.

All in polynomial time.


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# Witness and Graph Coloring

The information provided must be something we could have come up with ourselves, but probably at an exponential cost. And, it has to be enough so that we can conclude the final answer Yes from it.

Consider a witness for the graph coloring problem:

Given: A graph **G = (V, E)** and an integer **k**.

Question: Can the vertices of **G** be assigned colors so that adjacent vertices have different colors and use at most **k** colors?


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# Good and Bad Witnesses

The witness could just say Yes or No.

But that's not good enough - we don't know of a polynomial algorithm for graph coloring.

It could be "vertex 10 is colored Red."

That's not good enough either. Any single vertex can be colored any color we want.

It could be a color assigned to each vertex.

That would work, because we can verify its validity in polynomial time, and we can conclude the correct answer of Yes.

# More on Witnesses

What if it was a color for all vertices but one?

That also is enough. We can verify the correctness of the **n-1** given to us, then we can verify that the one uncolored vertex can be colored with a color not on any neighbor, and that the total is not more than **k**.

What if all but 2, 3, or 20 vertices are colored

All are valid witnesses. (Potentially exponential but for a constant, not a variable **n**)

What if half the vertices are colored?

Usually,  No. There's not enough information. Sure, we can check that what is given to us is properly colored, but we don't know how to "finish it off" except perhaps in $\mathbf{k^{n/2}}$ time.


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# Deterministic Exponential Time

A major question remains: Do we have, in NDTMs, a model of computation that solves all deterministic exponential (DE) problems in polynomial time (nondeterministic polynomial time)??

It definitely solves some problems we *think* are DE in nondeterministic polynomial time.


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# DEXP Versus NEXP

But, so far, all problems that have been proven to require deterministic exponential time also require nondeterministic exponential time.

So, the jury is still out. In the meantime, NDTMs are still valuable, because they might identify a larger class of problems than does a deterministic TM - the set of decision problems for which Yes instances can be verified in polynomial time.

# Problem Classes

We now begin to discuss several different classes of problems. The first two will be:

| | |
|---|---|
| **NP** | 'Nondeterministic' Polynomial |
| **P** | 'Deterministic' Polynomial,<br>The 'easiest' problems in NP |

Their definitions are rooted in the depths of Computability Theory as just described, but it is worth repeating some of it in the next few slides.



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# Class – NP

**First Significant Complexity Class of Problems**

# Vertex Cover Definition

Consider two seemingly closely related statements (versions) of a single problem. We show they are actually very different. Let **G = (V, E)** be a graph.

**Definition: X** $\subseteq$ **V(G)** is a *vertex cover* if every edge in **G** has at least one endpoint in **X.**

# Variants of VC

**Version 1.** Given a graph **G** and an integer **k.**
Does **G** contain a vertex cover
with at most **k** vertices?

**Version 2.** Given a graph **G** and an integer **k.**
Does the smallest vertex cover of **G**
have exactly **k** vertices?

Suppose, for either version, the answer is **"yes,"** and someone also gives us a set **X** of vertices and claims

**"X satisfies the conditions."**


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# Version 1 of VC

In **Version 1**, we can easily check that the claim is correct – in polynomial time.

That is, in polynomial time, we can check that **X** has **k** vertices, and that **X** is a vertex cover.

# Version 2 of VC

In **Version 2**, we can also easily check that X has exactly **k** vertices and that **X** is a vertex cover.

<u>But</u> we don't know how to easily check that there is not a smaller vertex cover!!

That seems to require exponential time.

These are very similar *looking* "decision" problems (Yes/No answers), yet they are VERY different in this one important respect.

# Version 1 in NP

**Version 1** problems make up the class called **NP**

**Definition:** The *Class **NP*** is the set of all decision problems for which answers to Yes instances can be verified in polynomial time.

For historical reasons, **NP** means

**"Nondeterministic Polynomial."**

*(Specifically, it does not mean "not polynomial").*

# Version 3 of VC

**Version 2** of the Vertex Cover problem is not unique. There are other versions that exhibit this same property. For example,

**Version 3:** Given: A graph **G = (V, E)** and an integer **k**.

**Question:** Do all vertex covers of **G** have more than **k** vertices?

What would/could a 'witness' for a Yes instance be?

**Version 3** is the Complement Problem of **Version 1**. It is a “for all not” versus a “there exist.”

# Characteristics of NP

All problems in **NP** are ***decidable*.**

That means there is an algorithm.

And the algorithm is no worse than **O($2^n$).**

# Non-NP

**Version 2** and **3 problems** are apparently not in **NP**.

So, where are they??

We need more structure! {Again, later.}

First we look inward, within **NP**.

# Class – P

**Second Significant Complexity Class of Problems**

# P Contained in NP

Some decision problems in **NP** can be solved (without knowing the answer in advance) - in polynomial time. That is, not only can we verify a correct answer in polynomial time, but we can actually compute the correct answer in polynomial time - from "scratch."

These are the problems that make up the class **P**.

**P** is a subset of **NP**.

# A Witness Analogy for P

Problems in **P** can also have a witness – we just don't need one. This line of thought leads to an interesting observation.

**Given:** A list **L** of **n** values and a key **X**.

**Question:** Is **X** in **L**?

An oracle can provide a "witness" for a **Yes** instance by writing the index **k** for **X**.

We can verify the correctness with one simple comparison Is **L[k] = X**?

# Complement of P

Now, consider the complement (**Version 3)** of this problem:

**Given:** A list **L** of **n** values and a key **X.**

**Question:** Is **X** not in **L**?

Here, for any Yes instance, no 'witness' seems to exist, but if the oracle simply writes down "Yes" we can verify the correctness in polynomial time by comparing **X** with each of the **n** values and report "Yes, **X** is not in the list“ if that is so.


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# P and Co-P

Therefore, both problems can be verified in polynomial time and, hence, both are in **NP**.

This is a characteristic of any problem in **P** - both it and its complement can be verified in polynomial time (of course, they can both be 'solved' in polynomial time, too.)

Therefore, we can again conclude **P** $\subseteq$ **NP.**


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# NP and Co-NP

There is a popular conjecture that if any problem and its complement are both in **NP**, then both are also in **P**.

This has been the case for several problems that for many years were not known to be in **P**, but both the problem and its complement were known to be in **NP**.

For example, Linear Programming (proven to be in **P** in the 1980’s).

A notable 'holdout' to date is Graph Isomorphism.

# Is P=NP?

At the moment, no one knows.

Some believe all problems in **NP** have polynomial algorithms. Many do not (believe that).

The fundamental question in theoretical computer science is:

Does **P = NP?**

There is an award of one million dollars for a proof.

– Either way, True or False.


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# The "Key" to Complexity Theory

**'Reductions,'**
**'Reductions,'**
**'Reductions.'**

# Abstract Solution

For any problem **X**, let **X($I_X$, $Answer_X$)** represents an algorithm for problem **X** – even if none is known to exist.

> **$I_X$** is an arbitrary instance given to the algorithm and **$Answer_X$** is the returned answer determined by the algorithm.



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# Polynomial Time Reductions

**Definition:** For problems **A** and **B**, a (*Polynomial) Turing Reduction* is an algorithm **A($I_A$, $Answer_A$)** for solving all instances of problem **A** and satisfies the following:

(1) Constructs zero or more instances of problem **B** and invokes algorithm **B($I_B$, $Answer_B$)**, on each.

(2) Computes the result, **$Answer_A$**, for **$I_A$**.

(3) Except for the time required to execute algorithm **B**, the execution time of algorithm **A** must be polynomial with respect to the size of **$I_A$**.

We say **$A \le_P B$**

# Best Algorithm for B

We may <u>assume</u> a 'best' algorithm for problem **B** without actually knowing it.

If **A($I_A$, $Answer_A$)** can be written without algorithm **B**, then problem **A** is simply a polynomial problem.

# PolyTime Reductions

**Theorem.** If **A** $\leq_P$ **B** and problem **B** is polynomial, then problem **A** is polynomial.

**Corollary.** If **A** $\leq_P$ **B** and problem **A** is exponential, then problem **B** is exponential.


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# PT Reduction Theorem

***Theorem.*** If $\mathbf{A} \leq_{\mathbf{P}} \mathbf{B}$ , then problem A is "no harder than" problem **B**.

***Proof:*** Let $\mathbf{f_X(n)}$ be the inherent complexity of problem **X**. Let $\mathbf{t_A(n)}$ and $\mathbf{t_B(n)}$ be the maximum times for some algorithms to solve **A** and **B.** Thus, $\mathbf{f_A(n) \leq t_A(n)}$**.** Further, since we assume the best algorithm for **B**, $\mathbf{t_B(n) = f_B(n)}$**.** Since $\mathbf{A} \leq_{\mathbf{P}} \mathbf{B}$, there is a constant **k** such that $\mathbf{t_A(n) \leq n^k t_B(n)}$**.** Therefore, $\mathbf{f_A(n) \leq t_A(n) \leq n^k t_B(n) = n^k f_B(n)}$**.** That is, **A** is no harder than **B** within a polynomial factor.



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# PT Reductions Properties

**Theorem. (transitivity)**

**If A $\le_P$ B and B $\le_P$ C then A $\le_P$ C.**

**Definition.**

**If A $\le_P$ B and B $\le_P$ A, then A and B are *polynomially equivalent*. A$\equiv_p$B**

**Note reflexive as A $\le_P$ A**

# NP–Complete

## Third Significant Complexity Class of Problems

# NP–Complete

- Polynomial Transformations enforce an equivalence relationship on all decision problems, particularly, those in the Class NP. Class P is one of those classes and is the "easiest" class of problems in NP.
- Is there a class in **NP** that is the hardest class in **NP**?
- A problem **B** in **NP** such **that A** $\leq_P$ **B** for every **A** in **NP** is called **NP-Complete**
  (Analogy to re-complete)

# NP–Hard

- A problem **B** such **that A $\le_P$ B** for every **A** in **NP-Complete** is called **NP-Hard**
  (Second Analogy to re-hard)



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# Propositional Logic

How Hard Can That Be?

# Propositional Calculus

- Mathematical of unquantified logical expressions
- Essentially Boolean algebra
- Goal is to reason about propositions
- Often interested in determining
  - Is a well-formed formula (wff) a tautology?
  - Is a wff refutable (unsatisfiable)?
  - Is a wff satisfiable? (will show this is the canonical NP-complete problem)

# Tautology and Satisfiability

- The classic approaches are:
  - Truth Table
  - Axiomatic System (axioms and inferences)
- Truth Table
  - Clearly exponential in number of variables
- Axiomatic Systems Rules of Inference
  - Substitution and Modus Ponens
  - Resolution / Unification ($1^{st}$ order only)

# Proving Consequences

- Start with a set of axioms (all tautologies)
- Using substitution and MP
  $(P, P \supset Q \Rightarrow Q)$
  derive consequences of axioms (also tautologies, but just a fragment of all unless axioms are "complete")
- Can create complete sets of axioms
- Need 3 variables for associativity, e.g.,
  $(p1 \vee p2) \vee p3 \quad \supset \quad p1 \vee (p2 \vee p3)$

# Some Undecidables

- Given a set of axioms,
  - Is this set complete?
  - Given a tautology **T**, is **T** a consequent?
- The above are even undecidable with one axiom and with only 2 variables. I will show the latter result shortly.

# Refutation

- If we wish to prove that some wff, F, is a tautology, we could negate it and try to prove that the new formula is refutable (cannot be satisfied; contains a logical contradiction).
- This is often done using resolution.


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# Resolution

- Put formula in Conjunctive Normal Form (CNF)
- If have terms of conjunction
  $(P \vee Q), (R \vee \sim Q)$
  then can determine that $(P \vee R)$
- If we ever get a null conclusion, we have refuted the proposition
- Resolution is not complete for derivation, but it is for refutation

# Axioms

- Must be tautologies
- Can be incomplete
- Might have limitations on them and on WFFs, e.g.,
  - Just implication
  - Only n variables
  - Single axiom

# Simulating Machines

- Linear representations require associativity, unless all operations can be performed on prefix only (or suffix only)
- Prefix and suffix-based operations are single stacks and limit us to CFLs
- Can simulate Post normal Forms with just 3 variables. A PNF has rules $\alpha P \rightarrow P\beta$


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# Diadic PIPC

- Diadic limits us to two variables
- PIPC means Partial Implicational Propositional Calculus, and limits us to implication as only connective
- Partial just means we get a fragment
- Problems
  - Is fragment complete?
  - Can F be derived by substitution and MP?

# Living without Associativity

- Consider a two-stack model of a TM
- Could somehow use one variable for left stack and other for right
- Must find a way to encode a sequence as a composition of forms – that's the key to this simulation

# Composition Encoding

- Consider $(p \supset p)$, $(p \supset (p \supset p))$, $(p \supset (p \supset (p \supset p)))$, …
  - No form is a substitution instance of any of the other, so they can't be confused
  - All are tautologies
- Consider $((X \supset Y) \supset Y)$
  - This is just $X \vee Y$


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# Encoding

- Use $(p \supset p)$ as form of bottom of stack
- Use $(p \supset (p \supset p))$ as form for letter 0
- Use $(p \supset (p \supset (p \supset p)))$ as form for 1
- Etc.
- String 01 (reading top to bottom of stack) is
  - $( \; ( (p \supset p) \supset ( (p \supset p) \supset ( (p \supset p) \supset (p \supset p) ) ) ) \supset$
    $( ( (p \supset p) \supset ( (p \supset p) \supset ( (p \supset p) \supset (p \supset p) ) ) ) \supset$
    $( (p \supset p) \supset ( (p \supset p) \supset ( (p \supset p) \supset (p \supset p) ) ) ) )$

# TM to Encode

- Tape alphabet {0,1}      0 is blank
- State set $\{q_1, q_2, \dots, q_m\}$
  - $q_1$ is start state
  - Machine halts if we reach a discriminant (state, scanned symbol) with no associated action


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# Encoding Functions

$\mathrm{I}(p)$ abbreviates $[p \supset p]$ // stack bottom

$\Phi_0(p)$ is $[p \supset \mathrm{I}(p)]$ which is $[p \supset [p \supset p]]$ // symbol 0

$\Phi_1(p)$ is $[p \supset \Phi_0(p)]$ // symbol 1

$\xi_1(p)$ is $[p \supset \Phi_1(p)]$ // helper 1

$\xi_2(p)$ is $[p \supset \xi_1(p)]$ // helper 2

$\xi_3(p)$ is $[p \supset \xi_2(p)]$ // helper 3

$\psi_1(p)$ is $[p \supset \xi_3(p)]$ // symbol $q_1$

$\psi_2(p)$ is $[p \supset \psi_1(p)]$ // symbol $q_2$

…

$\psi_m(p)$ is $[p \supset \psi_{m-1}(p)]$ // symbol $q_m$


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# Example TM ID

- Let a TM's ID be
  110 $q_5$ 1101
- Tape could be represented by two stacks
  Stack 1 is right side, reading left to right
  $q_5$ 1101
- Stack 2 is left side, reading right to left
  011

# Excoded Example TM ID

- $q_5$ 1101 (stack 1, read left to right)
- 011 (stack 2, read left to right)
- $\psi_5( \Phi_1( \Phi_1( \Phi_0( \Phi_1( I (p_1) ) ) ) ) ) \vee \Phi_0( \Phi_1( \Phi_1( I (p_2) ) ) )$
- Consider a Turing Table entry $q_5$ 1 L $q_2$
- We could have an implication like
  $[\psi_5(\Phi_1(p_1)) \vee \Phi_0(p_2)] \supset [\psi_2(\Phi_0(\Phi_1(p_1))) \vee p_2]$
- Using substitution (see red) and MP
  $[\psi_5(\Phi_1(\Phi_1(\Phi_0(\Phi_1(I(p_1)))))) \vee \Phi_0(\Phi_1(\Phi_1(I(p_1))))] \Rightarrow$
  $[\psi_5(\Phi_0(\Phi_1(\Phi_1(\Phi_0(\Phi_1(I(p_1))))))) \vee \Phi_1(\Phi_1(I(p_1)))]$
- This mimics one step of forward computation


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# Running Backwards

- The simulation we show actually will mimic the TM running backwards so the rule on the previous page will actually be
  $[\psi_2(\Phi_0(\Phi_1(p_1))) \vee p_2] \supset [\psi_5(\Phi_1(p_1)) \vee \Phi_0(p_2)]$
- To kick things off, my rules want to allow me to deduce any arbitrary halting ID
- We use three helper forms to do this; they are $\xi_1(p)$, $\xi_2(p)$, and $\xi_3(p)$

# $\xi_1$ Sets Up Stack 2

- The only axiom that does not involve a form for which MP can be applied is
  **1. $[\xi_1 I(p_1) \vee I(p_1)]$**
- The above reflects two empty stacks
- Using $\xi_1$ rules, we generate any and all possible left-hand sides of tape in stack 2
- This guarantees that left side is either empty (rule 4) or starts with a 1 (rule 2)
- If we apply rule 2 then rule 3 can expand the left side

1. $[\xi_1 I(p_1) \vee I(p_1)]$.
2. $[\xi_1 I(p_1) \vee I(p_1)] \supset [\xi_1 I(p_1) \vee \Phi_1 I(p_1)]$.
3. $[\xi_1 I(p_1) \vee \Phi_i(p_2)] \supset [\xi_1 I(p_1) \vee \Phi_j \Phi_i(p_2)], \forall i, j \in \{0, 1\}$.
4. $[\xi_1 I(p_1) \vee p_2] \supset [\xi_2 \Phi_1 I(p_1) \vee p_2]$.
5. $[\xi_1 I(p_1) \vee p_2] \supset [\xi_3 \Phi_i I(p_1) \vee p_2], \forall i \in \{0, 1\}$.


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# $\xi_2$ Starts Up Stack1

- Two possibilities follow
  Either Rule 4 replaces $\xi_1$ with $\xi_2$ and assures that the right side of tape (stack 1) has a 1 as its leftmost symbol
  Or Rule 5 replaces $\xi_1$ with $\xi_3$ and assures that the right side of tape (stack 1) has just a scanned symbol (can be a 0 or 1)
- If we use $\xi_2$ then rule 6 can expand the right side but at some point we use rule 7 to switch to $\xi_3$

6. $[\xi_2\Phi_i(p_1) \vee p_2] \supset [\xi_2\Phi_j\Phi_i(p_1) \vee p_2], \forall i, j \in \{0, 1\}.$
7. $[\xi_2\Phi_i(p_1) \vee p_2] \supset [\xi_3\Phi_j\Phi_i(p_1) \vee p_2], \forall i, j \in \{0, 1\}.$


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# $\xi_3$ Insures Terminal Discriminamt

- Rule 8 replaces $\xi_3$ with any $\psi_k$ such that $\mathbf{q_k i}$ halts (no rule) and i, represented by $\Phi_i$, is on the top of stack 1 (new wff will be of form $\psi_k(\Phi_i(\mathbf{p_1})) \vee \mathbf{p_2}$
- This is the point where the simulation of the TM begins, except we run TM in reverse via rules 9-13 (and their subparts)
- While these rules can be a bit complex at first they are just the same ones we used to map a TM to a semi-Thue system or a PSG

8. $[\xi_3\Phi_i(p_1) \vee p_2] \supset [\Psi_k\Phi_i(p_1) \vee p_2]$, whenever $q_k a_i$ is a terminal discriminant of $M$.

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# Putting it Together

- The main point is that the axioms produce a bunch of items that are easy to check for validity (the stuff involving the forms $\xi_1$, $\xi_2$, and $\xi_3$ plus exactly those representations of starting IDs for which the TM halts
- If we could decide what Tautologies are producible by this Propositional System then we would be able to solve the Halting Problem for TMs
- This proves the deducibility problem for Fragments of the 2-Variable Implicational Calculus (PIPC) is unsolvable
- This is true even though two variables are insufficient to represent the basic notion of associativity!!!

# Creating Terminal IDs

1. $[\xi_1 I(p_1) \vee I(p_1)]$.
2. $[\xi_1 I(p_1) \vee I(p_1)] \supset [\xi_1 I(p_1) \vee \Phi_1 I(p_1)]$.
3. $[\xi_1 I(p_1) \vee \Phi_i(p_2)] \supset [\xi_1 I(p_1) \vee \Phi_j \Phi_i(p_2)]$, $\forall i, j \in \{0, 1\}$.
4. $[\xi_1 I(p_1) \vee p_2] \supset [\xi_2 \Phi_1 I(p_1) \vee p_2]$.
5. $[\xi_1 I(p_1) \vee p_2] \supset [\xi_3 \Phi_i I(p_1) \vee p_2]$, $\forall i \in \{0, 1\}$.
6. $[\xi_2 \Phi_i(p_1) \vee p_2] \supset [\xi_2 \Phi_j \Phi_i(p_1) \vee p_2]$, $\forall i, j \in \{0, 1\}$.
7. $[\xi_2 \Phi_i(p_1) \vee p_2] \supset [\xi_3 \Phi_j \Phi_i(p_1) \vee p_2]$, $\forall i, j \in \{0, 1\}$.
8. $[\xi_3 \Phi_i(p_1) \vee p_2] \supset [\Psi_k \Phi_i(p_1) \vee p_2]$, whenever $q_k a_i$ is a terminal discriminant of $M$.

# Reversing Print and Left

9. $[\Psi_k\Phi_i(p_1) \vee p_2] \supset [\Psi_h\Phi_j(p_1) \vee p_2]$, whenever $q_h a_j a_i q_k \in T$.

10a. $[\Psi_k\Phi_0 I(p_1) \vee I(p_1)] \supset [\Psi_h\Phi_0 I(p_1) \vee I(p_1)]$,

b. $[\Psi_k\Phi_1 I(p_1) \vee I(p_1)] \supset [\Psi_h\Phi_0 I(p_1) \vee \Phi_1(p_1)]$,

c. $[\Psi_k\Phi_i I(p_1) \vee \Phi_j(p_2)] \supset [\Psi_h\Phi_0 I(p_1) \vee \Phi_i\Phi_j(p_2)]$,

d. $[\Psi_k\Phi_0\Phi_0\Phi_i(p_1) \vee I(p_2)] \supset [\Psi_h\Phi_0\Phi_i(p_1) \vee I(p_2)]$,

e. $[\Psi_k\Phi_1\Phi_0\Phi_i(p_1) \vee I(p_2)] \supset [\Psi_h\Phi_0\Phi_i(p_1) \vee \Phi_1 I(p_2)]$,

f. $[\Psi_k\Phi_i\Phi_0\Phi_j(p_1) \vee \Phi_m(p_2)] \supset [\Psi_h\Phi_0\Phi_j(p_1) \vee \Phi_i\Phi_m(p_2)]$,

$\forall i, j, m \in \{0, 1\}$ whenever $q_h 0 L q_k \in T$.

11a. $[\Psi_k\Phi_0\Phi_1(p_1) \vee I(p_2)] \supset [\Psi_h\Phi_1(p_1) \vee I(p_2)]$,

b. $[\Psi_k\Phi_1\Phi_1(p_1) \vee I(p_2)] \supset [\Psi_h\Phi_1(p_1) \vee \Phi_1 I(p_2)]$,

c. $[\Psi_k\Phi_i\Phi_1(p_1) \vee \Phi_j(p_2)] \supset [\Psi_h\Phi_1(p_1) \vee \Phi_i\Phi_j(p_2)]$,

$\forall i, j \in \{0, 1\}$ whenever $q_h 1 L q_k \in T$.

# Reversing Right

12a. $[\Psi_k\Phi_0 I(p_1) \vee I(p_1)] \supset [\Psi_h\Phi_0 I(p_1) \vee I(p_1)]$,

b. $[\Psi_k\Phi_0 I(p_1) \vee \Phi_0\Phi_i(p_2)] \supset [\Psi_h\Phi_0 I(p_1) \vee \Phi_i(p_2)]$,

c. $[\Psi_k\Phi_1(p_1) \vee I(p_2)] \supset [\Psi_h\Phi_0\Phi_1(p_1) \vee I(p_2)]$,

d. $[\Psi_k\Phi_0\Phi_i(p_1) \vee I(p_2)] \supset [\Psi_h\Phi_0\Phi_0\Phi_i(p_1) \vee I(p_2)]$,

e. $[\Psi_k\Phi_0\Phi_i(p_1) \vee \Phi_0\Phi_j(p_2)] \supset [\Psi_h\Phi_0\Phi_0\Phi_i(p_1) \vee \Phi_j(p_2)]$,

f. $[\Psi_k\Phi_1(p_1) \vee \Phi_0\Phi_i(p_2)] \supset [\Psi_h\Phi_0\Phi_1(p_1) \vee \Phi_i(p_2)]$,

$\forall i, j \in \{0, 1\}$ whenever $q_h 0 R q_k \in T$.

13a. $[\Psi_k\Phi_0 I(p_1) \vee \Phi_1(p_2)] \supset [\Psi_h\Phi_1 I(p_1) \vee p_2]$,

b. $[\Psi_k\Phi_1(p_1) \vee \Phi_1(p_2)] \supset [\Psi_h\Phi_1\Phi_1(p_1) \vee p_2]$,

c. $[\Psi_k\Phi_0\Phi_i(p_1) \vee \Phi_1(p_2)] \supset [\Psi_h\Phi_1\Phi_0\Phi_i(p_1) \vee p_2]$

$\forall i \in \{0, 1\}$ whenever $q_h 1 R q_k \in T$.

# Satisfiability

How Hard Can That Be?

# Conjunctive Normal Form

**$U = \{u_1, u_2, \ldots, u_n\}$, Boolean variables.**

**$C = \{c_1, c_2, \ldots, c_m\}$, "OR clauses"**

**For example:**

$$c_i = (u_4 \lor u_{35} \lor \sim u_{18} \lor u_3 \ldots \lor \sim u_6)$$


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# Satisfiability Challenge

Can we assign Boolean values to the variables in **U** so that every clause is **TRUE**?

There is no known polynomial time algorithm!!


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# Cook's Theorem

***<u>Cooks Theorem:</u>***

**1) SAT is in NP**

**2) For every problem A in NP,**

$$A \leq_P SAT$$

**Thus, SAT is as hard as every problem in NP.**

# SAT as NP–Complete

**Since SAT is itself in NP, that means SAT is a hardest problem in NP (there can be more than one.).**

**A hardest problem in a class is called the "completion" of that class.**

**Therefore, SAT is NP–Complete.**


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# Ubiquity

Today, there are 1,000's of problems that have been proven to be NP–Complete. (See Garey and Johnson, *Computers and Intractability: A Guide to the Theory of NP–Completeness*, for a list of over 300 as of the early 1980's).

# What about P = NP?

If P = NP then all problems in NP are polynomial problems.

If P ≠ NP then all NP–C problems are at least super-polynomial and perhaps exponential. That is, NP-C problems could require sub-exponential super-polynomial time. (Example of super-polynomial, sub-exponential is $\mathbf{o(2^{o(n)})}$, e.g., $\mathbf{2^{\sqrt[3]{n}}}$


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don't seem to be solvable in polynomial time.
- Many smart people have tried for a long time to find polynomial algorithms for some of the problems in NP-Complete - with no luck.

# Evidence for P = NP?

Why should P equal NP?

- There seems to be a huge "gap" between the known problems in P and Exponential. That is, almost all known polynomial problems are no worse than $n^3$ or $n^4$.
- Where are the $O(n^{50})$ problems?? $O(n^{100})$? Maybe they are the ones in NP–Complete?
- It's awfully hard to envision a problem that would require $n^{100}$, but surely they exist?
- Some of the problems in NP–C just look like we should be able to find a polynomial solution (looks can be deceiving, though).

# Evidence for $P \neq NP$?

**Why should P not equal NP?**

- P = NP would mean, for any problem in NP, that it is just as easy to solve an instance form "scratch," as it is to verify the answer if someone gives it to you. That seems a bit hard to believe.
- There simply are a lot of awfully hard looking problems in NP–Complete (and Co–NP-Complete) and some just don't seem to be solvable in polynomial time.
- Many smart people have tried for a long time to find polynomial algorithms for some of the problems in NP-Complete - with no luck.


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# NP-Complete; NP-Hard

A decision problem, *C*, is NP-complete if:

C is in NP and

C is NP-hard. That is, every problem in NP is polynomially reducible to C.

*D* polynomially reduces to *C* means that there is a deterministic polynomial-time many-one algorithm, *f*, that transforms each instance *x* of *D* into an instance f(x) of *C*, such that the answer to *f(x)* is YES if and only if the answer to *x* is YES.

To prove that an NP problem *A* is NP-complete, it is sufficient to show that an already known NP-complete problem polynomially reduces to *A*. By transitivity, this shows that *A* is NP-hard.

A consequence of this definition is that if we had a polynomial time algorithm for any NP-complete problem *C*, we could solve all problems in NP in polynomial time. That is, P = NP.

Note that NP-hard does not necessarily mean NP-complete, as a given NP-hard problem could be outside NP. Analogy to re-complete

# Returning to SAT

- SAT is the problem to decide of an arbitrary Boolean formula (wff in the propositional calculus) whether or not this formula is satisfiable (has a set of variable assignments that evaluate the expression to true).
- SAT clearly can be solved in time $k2^n$, where k is the length of the formula and n is the number of variables in the formula.
- What we now show is that SAT is NP-complete, providing us our first concrete example of an NP-complete decision problem.

# Simulating NDTM

- Given a NDTM, **M**, and an input **w**, we need to create a formula, $\varphi_{M,w}$, containing a polynomial number of terms that is satisfiable just in case **M** accepts **w** in polynomial time.
- The formula must encode within its terms a trace of configurations that includes
  - A term for the starting configuration of the TM
  - Terms for all accepting configurations of the TM
  - Terms that ensure the consistency of each configuration
  - Terms that ensure that each configuration after the first follows from the prior configuration by a single move

# Tableaus

A **tableau** is an array of tape alphabet symbols.

- It represents a configuration history of **one branch** of our NDTM's nondeterminism.
- If the NDTM runs in $n^k$ time, the tableau is an $(n^k \times n^k)$ tableau.
  - It's big enough downward because, well, the TM runs in $n^k$.
  - …and rightward because the TM can only *count* to $n^k$.
- We assume that every configuration starts and ends with a # symbol.
- We think of our tableau as looking like this in the "beginning": the starting configuration across the top, and the other configurations blank.
  - (We quote "beginning" because SAT isn't really a stateful algorithm, but just go with it for now.)
- But we've assumed that we can "represent" alphabet symbols. How do we do that, in *SAT*?

| # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # | |
|---|---|---|---|---|---|---|---|---|---|---|
| # | | | | | | | | | # | |
| # | | | | | | | | | # | |
| # | | | | | | | | | # | |
| # | | | | | | | | | # | |
| # | | | | | | | | | # | $\uparrow n^k \downarrow$ |
| # | | | | | | | | | # | |
| # | | | | | | | | | # | |
| # | | | | | | | | | # | |
| # | | | | | | | | | # | |
| $\leftarrow n^k \rightarrow$ | | | | | | | | | | |

# Encoding the Tableau: Basics

Consider a set comprised of:

The tape alphabet

The state set

The separator character

$$C = \Gamma \cup Q \cup \{ \# \}$$

Consider a cell variable:

$$x_{i,j,c}$$

***Turning this variable on*** *corresponds to* ***setting cell (i, j) = c***, for some $c \in C$.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # |
| 2 | # | | | | | | | | | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |


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# Encoding the Tableau: Cells

Consider our tableau alphabet:

$$C = \Gamma \cup Q \cup \{ \# \}$$

Consider a cell and corresponding variable:

$$x_{i,j,c}$$

Now we need to make sure the tableau is consistently encoded.

Create a clause for **each cell (*i*, *j*)**.

$$\phi_{\text{encode}}(i,j) = \left[ \left( \bigvee_{c \in C} x_{i,j,c} \right) \wedge \left( \bigwedge_{\substack{c,d \in C \\ c \neq d}} \left( \overline{x_{i,j,c}} \vee \overline{x_{i,j,d}} \right) \right) \right]$$

The left demands $x_{i,j,c}$ be true for **some *c*.**
The right demands $x_{i,j,c}$ be true for **only one *c*.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # |
| 2 | # | | | | | | | | | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |

# Encoding the Tableau: The Tableau

Tableau alphabet: $C = \Gamma \cup Q \cup \{ \# \}$

Cell variable: $x_{i,j,c}$

Create an encoding clause for each cell (i, j).

$$\phi_{\text{encode}}(i,j) = \left[ \left( \bigvee_{c \in C} x_{i,j,c} \right) \wedge \left( \bigwedge_{\substack{c,d \in C \\ c \neq d}} \left( \overline{x_{i,j,c}} \vee \overline{x_{i,j,d}} \right) \right) \right]$$

Now repeat the clause across the tableau.

$$\phi_{\text{cells}} = \bigwedge_{1 \le i,j \le n^k} \phi_{\text{encode}}(i,j)$$

**This is our *cell formula*. It ensures that each cell in the tableau is assigned a single symbol.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # |
| 2 | # | | | | | | | | | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |


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# Encoding the Tableau: Complexity

$$\phi_{\text{encode}}(i,j) = \left[\left(\bigvee_{c\in C} x_{i,j,c}\right) \wedge \left(\bigwedge_{\substack{c,d\in C\\ c\neq d}} \left(\overline{x_{i,j,c}} \vee \overline{x_{i,j,d}}\right)\right)\right]$$

We can create the single-cell encoding formula in polynomial time with a $|C|^2$ iteration.

$$\phi_{\text{cells}} = \bigwedge_{1\le i,j\le n^k} \phi_{\text{encode}}(i,j)$$

We can create the *entire* cell formula in polynomial time with an $n^{2k}$ iteration around that.

So we can say that $\phi_{\text{cells}}$ **is satisfied by, and only by, a properly encoded tableau, and is created in polynomial time.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # |
| 2 | # | | | | | | | | | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |

# Starting and Accepting

Starting and accepting are (comparatively) easy.

To start, take the start configuration padded to $n^k$ length with blanks…

$S = \#q_0w_1w_2\ldots w_n\square\ldots\square\#$ so that $|S| = n^k$

…and **require the first row be equal to the start configuration**:

$$\phi_{\text{start}} = \bigwedge_{1 \le j \le n^k} \left[x_{1,j,s_j}\right]$$

Then to accept, just **require an accept state somewhere in the tableau.**

$$\phi_{\text{accept}} = \bigvee_{1 \le i,j \le n^k} \left[x_{i,j,q_\text{A}}\right]$$

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # |
| 2 | # | | | | | | | | | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | $w_1$ | $w_2$ | … | $q_A$ | … | □ | … | □ | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |

# Starting and Accepting

$$\phi_{\text{start}} = \bigwedge_{1 \le j \le n^k} [x_{1,j,s_j}]$$

$$\phi_{\text{accept}} = \bigvee_{1 \le i,j \le n^k} [x_{i,j,q_A}]$$

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | $w_1$ | $w_2$ | … | $w_n$ | □ | … | □ | # |
| 2 | # |  |  |  |  |  |  |  |  | # |
| 3 | # |  |  |  |  |  |  |  |  | # |
| 4 | # |  |  |  |  |  |  |  |  | # |
| 5 | # | $z_1$ | $z_2$ | … | $q_A$ | … | □ | … | □ | # |
| 6 | # |  |  |  |  |  |  |  |  | # |
| 7 | # |  |  |  |  |  |  |  |  | # |
| 8 | # |  |  |  |  |  |  |  |  | # |
| 9 | # |  |  |  |  |  |  |  |  | # |
| 10 | # |  |  |  |  |  |  |  |  | # |

We can generate the start and accept formulas in $n^k$ and $(n^k)^2$ time, both polynomial.

So now we can say that:

**$\phi_{\text{start}}$ is satisfied by, and only by, a tableau with the starting configuration of *M* on *w* encoded as its first row, and is created in polynomial time.**

…and…

**$\phi_{\text{accept}}$ is satisfied by, and only by, a tableau encoding an accepting configuration as one of its rows, and is created in polynomial time.**

# Transitions

Now, for transitions. Recall the discussions we had about ID changes being limited to three characters or six, when looking at transitions..

> A given 2x3 **window** is **legal** if it does not violate our machine's transition function.
>
> Given the linear sets of states and tape symbols, and the finite size of 2x3 windows, we can make a **polynomial-sized set of all legal windows**.

Let a sequence $A = (a_1, \ldots, a_6)$ be a 2x3 window, with $a_1$ the top left cell, $a_2$ the top middle, etc.

> We say that ***A* is *legal*** if it **represents a legal window**. Here we have $\mathbf{q_0\ a\ R\ q_1}$

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | *a* | *b* | c | *a* | □ | □ | □ | # |
| 2 | # | *a* | $q_1$ | *b* | c | *a* | □ | □ | □ | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |


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# Transitions

A given 2x3 **window** is **legal** if it does not violate our machine's transition function. We have a **polynomial-sized set of all legal windows**.

Let a sequence $A = (a_1, \ldots, a_6)$ be a 2x3 window. ***A* is *legal*** if it **represents a legal window**.

Now we can come up with a formula to say that the window top-centered at cell ($i$, $j$) is legal.

$$\phi_{\text{legal}}(i,j) = \bigvee_{\substack{A=(a_1,\ldots,a_6) \\ \text{is legal}}} \begin{bmatrix} x_{i,j-1,a_1} \wedge x_{i,j,a_2} \wedge x_{i,j+1,a_3} \wedge \\ x_{i+1,j-1,a_4} \wedge x_{i+1,j,a_5} \wedge x_{i+1,j+1,a_6} \end{bmatrix}$$

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | *a* | *b* | c | *a* | □ | □ | □ | # |
| 2 | # | *a* | $q_1$ | *b* | c | *a* | □ | □ | □ | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |

**Don't be intimidated by this formula!**

It's just **counting off the six cells of the window** and demanding that each be **equal to the corresponding cell** in **some legal window**.


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# Transitions

A given 2x3 **window** is **legal** if it does not violate our machine's transition function.

We have a **polynomial-sized set of all legal windows.**

Let a sequence $A = (a_1, \ldots, a_6)$ be a 2x3 window. ***A* is *legal*** if it **represents a legal window.**

$$\phi_{\text{legal}}(i,j) = \bigvee_{\substack{A=(a_1,\ldots,a_6) \\ \text{is legal}}} \begin{bmatrix} x_{i,j-1,a_1} \wedge x_{i,j,a_2} \wedge x_{i,j+1,a_3} \wedge \\ x_{i+1,j-1,a_4} \wedge x_{i+1,j,a_5} \wedge x_{i+1,j+1,a_6} \end{bmatrix}$$

Since we have a polynomial number of legal windows, this formula is also polynomial.  So we can say:

**$\phi_{\text{legal}}$ (*i, j*) is satisfied by, and only by, a tableau whose window top-centered at (*i, j*) is legal; and is created in polynomial time.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | *a* | *b* | c | *a* | □ | □ | □ | # |
| 2 | # | *a* | $q_1$ | *b* | c | *a* | □ | □ | □ | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |

# Windows and Configurations

Consider any **upper** and **lower** configuration in the tableau, so that the lower configuration is the one immediately below – that is, following – the upper.

If all the windows top-centered on cells in the upper configuration are legal, then:

- The legality of the windows that don't involve the state symbol easily ensures the legality of the configuration below them.
- The window top-centered on the state symbol in the upper configuration is sufficient to ensure that the state symbol in the lower configuration makes a legal move.

**The upper configuration yields the lower one if and only if all the windows top-centered on cells in the upper configuration are legal** – and that holds all the way down the tableau.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | *a* | *b* | c | *a* | □ | □ | □ | # |
| 2 | # | *a* | $q_1$ | *b* | c | *a* | □ | □ | □ | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |


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# Windows and Configurations

$$\phi_{\text{legal}}(i,j) = \bigvee_{\substack{A=(a_1,\ldots,a_6) \\ \text{is legal}}} \begin{bmatrix} x_{i,j-1,a_1} \wedge x_{i,j,a_2} \wedge x_{i,j+1,a_3} \wedge \\ x_{i+1,j-1,a_4} \wedge x_{i+1,j,a_5} \wedge x_{i+1,j+1,a_6} \end{bmatrix}$$

$\phi_{\text{legal}}$ $(i, j)$ is satisfied by, and only by, a tableau whose window top-centered at $(i, j)$ is legal; and is created in polynomial time.

An upper configuration yields a lower one iff all the windows top-centered within the upper are legal.

This holds all the way down the tableau.

Then we have:

$$\phi_{\text{move}} = \bigwedge_{\substack{1 \le i < n^k, \\ 1 < j < n^k}} \phi_{\text{legal}}(i,j)$$

And can say $\phi_{\text{move}}$ **is satisfied by, and only by, a tableau that does not violate the machine's transition function; and is created in polynomial time.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | # | $q_0$ | *a* | *b* | c | *a* | □ | □ | □ | # |
| 2 | # | *a* | $q_1$ | *b* | c | *a* | □ | □ | □ | # |
| 3 | # | | | | | | | | | # |
| 4 | # | | | | | | | | | # |
| 5 | # | | | | | | | | | # |
| 6 | # | | | | | | | | | # |
| 7 | # | | | | | | | | | # |
| 8 | # | | | | | | | | | # |
| 9 | # | | | | | | | | | # |
| 10 | # | | | | | | | | | # |


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# Pulling It Together

$$\phi_{\text{cells}} = \bigwedge_{1 \le i,j \le n^k} \phi_{\text{encode}}(i,j)$$

$$\phi_{\text{start}} = \bigwedge_{1 \le j \le n^k} \left[x_{1,j,s_j}\right]$$

$$\phi_{\text{accept}} = \bigvee_{1 \le i,j \le n^k} \left[x_{i,j,q_A}\right]$$

$$\phi_{\text{move}} = \bigwedge_{\substack{1 \le i < n^k, \\ 1 < j < n^k}} \phi_{\text{legal}}(i,j)$$

$$\phi_{\text{NDTM}} = \left(\phi_{\text{cells}} \wedge \phi_{\text{start}} \wedge \phi_{\text{accept}} \wedge \phi_{\text{move}}\right)$$

We have:

$\phi_{\text{cells}}$ is satisfied by, and only by, a properly encoded tableau.

$\phi_{\text{start}}$ is satisfied by, and only by, a tableau with the starting configuration of *M* on *w* encoded as its first row.

$\phi_{\text{accept}}$ is satisfied by, and only by, a tableau encoding an accepting configuration as one of its rows.

$\phi_{\text{move}}$ is satisfied by, and only by, a tableau that does not violate the machine's transition function.

All are created in polynomial time.

Then $\phi_{\text{NDTM}}$ **is satisfied by, and only by, a tableau encoding an accepting computation history of *M* on *w*, and is created in polynomial time.**


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# *SAT* is NP-Complete

$$\phi_{\text{NDTM}} = \left(\phi_{\text{cells}} \wedge \phi_{\text{start}} \wedge \phi_{\text{accept}} \wedge \phi_{\text{move}}\right)$$

$\phi_{\text{NDTM}}$ created from NDTM *M* and input *w* is satisfied by, and only by, a tableau encoding an accepting computation history of *M* on *w*, and is created in polynomial time.

This means that:

*SAT* accepts $\phi_{\text{NDTM}}$ if and only if such a tableau exists…

…if and only if the NDTM we are encoding into $\phi_{\text{NDTM}}$ accepts *w*.

We've just polynomially reduced every possible NP language to *SAT*.

Let's convince ourselves of that a bit more.

By definition, any NP language has an NDTM *M* that decides it in polynomial time.

**We can decide any NP language with a result from *SAT* using the following algorithm:**

**On input <*M*, *w*>:**

Create $\phi_{\text{NDTM}}$ from *M* and *w*.

Run the decider for *SAT* on $\phi_{\text{NDTM}}$.

Accept if *SAT* accepts, reject if it rejects.

***SAT* is NP-complete.**


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# Cook's Theorem

- $\varphi_{M,w} = \phi_{cells} \wedge \phi_{start} \wedge \phi_{accept} \wedge \phi_{move}$
- **See the following for another detailed description and discussion of the four terms that make up this formula.**
- http://www.cs.tau.ac.il/~safra/Complexity/Cook.ppt

# NP–Complete

Within a year, Richard Karp added 22 problems to this special class.

We will focus on:

- 3-SAT
- Integer Linear Programming
- SubsetSum
- Partition
- Vertex Cover
- Independent Set
- K-Color
- Multiprocessor Scheduling

# Co-NP

- A problem is in co-NP if its complement is in NP
  - This is like co-RE, with respect to RE problems.
- An example is the problem to determine if a Boolean expression is a tautology.
  - If the answer to the problem "is B in TAUT ?" is NO, then B is in the complement of SAT.
- A more direct example of a co-NP problem is to determine if a Boolean expression is self-contradictory.
  - This is the complement of the notion of satisfiability but not of an instance of satisfiability as the complement of an expression in SAT can also be in SAT.

# SAT to 3SAT

- 3-SAT means that each clause has exactly three terms
- If one term, e.g., (p), expand to $(p \vee p \vee p)$
- If two terms, e.g., $(p \vee q)$, expand to $(p \vee q \vee p)$
- Any clause with three terms is fine
- If n > three terms, can reduce to two clauses, one with three terms and one with n-1 terms, e.g., $(p1 \vee p2 \vee \ldots \vee pn)$ to
  $(p1 \vee p2 \vee z)$ & $(p3 \vee \ldots \vee pn \vee \sim z)$, where z is a new variable. If n=4, we are done, else apply this approach again with the clause having n-1 terms

# 3SAT Growth is Linear

- Let's make sure we have not grown the length of the expression going from an instance E of SAT to 3SAT by more than a polynomial amount.
- Let N be the number of clauses in E and let n be number of variables in E. Worst case length of E is then nN literals.
- If a clause in E has $k \geq 3$ literals, we want to define G(k)=number of literals in the 3SAT version, E'.
- G(3)=3; G(4)=G(3)+G(3)=6; G(5)=G(4)+G(3)=9; G(6)=G(5)+G(3)=12;…; G(k)=3(k-2), $k \geq 3$.
- The worst case is bounded above by 3nN literals in E' which is polynomial (linear) growth.

# Linear Programming (LP)

- Linear Programming (LP) is like solving a set of linear equations but allows not just equality (=) but also inequality (>, <, ≥, ≤)
- In fact, LP usually also includes an optimization function, but we are limiting ourselves to decision problems
- Example:
  $x + y > 7$
  $x - y \geq 4$
  Has many solutions, some of which are integral, e.g., $x=7$, $y=1$

# Integer LP (ILP)

- Integer Linear Programming (ILP) just constrains the solutions to an LP problem to be integral values
- This constraint, on the surface, may seem to make the problem easier but, in fact, makes it harder
- This is even true when we view this as a decision problem where we just ask
  "Is there a solution to this instance of ILP"
- We will see this complexity play out in the next few slides

# 0-1 ILP

- 0-1 ILP constrains the solution space to variable values of 0 or 1
- Start with an instance of SAT (or 3SAT), assuming variables $v1, \ldots, vn$ and clauses $c1, \ldots, cm$
- For each variable vi, have the constraint that $0 \le vi \le 1$
- For each clause we provide a constraint that it must be satisfied (evaluate to at least 1). For example, if clause cj is $v2 \lor \sim v3 \lor v5 \lor v6$ then add the constraint $v2 + (1-v3) + v5 + v6 \ge 1$
- A solution to this set of integer linear constraints implies a solution to the instance of SAT and vice versa
- Note this works for any SAT instance not just 3SAT


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# 0-1 ILP is NP-Complete

- Previous page just show 0-1 ILP is NP-Hard
- Must show it is in NP
- Can do by trying all $2^k$ 0-1 assignments to k variables
- Or can show that verifying a solution is in P – it's really just linear


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# 0-1 ILP Example

- **Original SAT: E = (a+b+~c+d+e)(~b)(~a+~d)(b+c+~e)**
- **$0 \le a \le 1$; $0 \le b \le 1$; $0 \le c \le 1$;**
  **$0 \le d \le 1$; $0 \le e \le 1$**
- **$a+b+(1-c)+d+e \ge 1$;**
  **alternatively, $a+b-c+d+e \ge 0$**
- **$1-b \ge 1$;**
  **alternatively, $b = 0$**
- **$(1-a)+(1-d) \ge 1$;**
  **alternatively, $a+d \le 1$**
- **$b+c+(1-e) \ge 1$;**
  **alternatively, $b+c-e \ge 0$**


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# What about ILP?

- As we said, ILP just constrains the solution to integers not to binary values
- Clearly ILP is NP-Hard as the constrained version of 0-1 ILP is NP-Hard
- Showing ILP is in NP is easy using a verifier; you give me a proposed solution and I can check it in linear time

# What about Linear Programming (LP) #1?

- Linear programming just requires that solution be real number values
- The only constraints are in the simultaneous inequalities (and equalities)
- If you limit LP to equalities, then it has a well-known complexity of $O(N^3)$ using Gaussian Elimination or one of its variants


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# What about Linear Programming (LP) #2?

- The problem of solving LP appeared to be exponential for a long time and was, and still is, generally attacked using the Simplex Method which involves adding slack variables, e.g.,
  $x + y < 7$ iff $x + y + e = 7$ for some $e > 0$ and
  $x + y \leq 7$ iff $x + y + f = 7$ for some $f \geq 0$
- One can show cases where the Simplex Method takes exponential time, but its average case is $O(N^{\sqrt{d}})$ time where N is the number of variables and d is bounded above by the size of the input in bits


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# What about Linear Programming (LP) #3?

- In 1984, LP was shown to be of polynomial complexity
- Complexity is $O(N^{3.5} L \lg L \lg\lg L)$ where N is number of variables and L is the size of the input in bits
- Simplex is still used much as QuickSort is used for sorting even though its worst case is $O(N^2)$ as its expected performance is $O(N \lg N)$ and it often converges in $O(N)$
- Note neither Simplex nor QuickSort are heuristics as each gives the correct result. I bring that up as later we will talk about heuristics for NP-Hard problems. There are some nice cases and some strange ones.

# SubsetSum

**$S = \{s_1, s_2, \ldots, s_n\}$**

set of positive integers

and an integer **G.**

**Question:** Does **S** have a subset whose values sum to the goal **G?**

**Note:** This is really a Bag (Multiset) not a Set

No one knows of a polynomial algorithm.

{No one has proven there isn't one, either!!}

# SubsetSum is in NP

- You give me a “solution” to [ $\{s_1, s_2, \ldots, s_n\}$, **G** ]
- Your solution is just a subset of the set of integers **{1 .. n}**
- I make sure that each number you give me is unique and in the correct range (that takes me n units of time). If not, I reject your “solution”
- I then add the selected numbers together. That takes the sum of the log based 2 of the numbers you selected. I then check that the sum equals **G**. If so, I verify; if not, I reject.
- Note that the original representation is of length the sum of the log based 2 of the $s_i$’s and **G** so my growth of time is linear
- Thus, I can verify in polynomial time

# Example SubsetSum

- Instance
  [(15, 17, 27, 11, 4, 12, 33, 5, 6, 21, 2), 57]
- A solution is 15, 17, 11, 12, 2 (or with indices just 1,2,4,6,11)
- Note that an item can only be chosen once
- Note that we can try a heuristic like sorting low to high
  [(2, 4, 5, 6, 11, 12, 15, 17, 21, 27, 33), 57]
- But an attack with that might have us choose
  2, 4, 5, 6, 11, 12, 15 and we are stuck
- In above, one can backtrack to remove 15 and replace by 17 works, but backtracking is in general exponential
- Try high to low [(33, 27, 21, 17, 15, 12, 11, 6, 5, 4, 2), 57]
  33, 27 (Fail), 33, 21, 17 (Fail), 33, 21, 15 (Fail), etc.
- Clearly all these are potentially exponential approaches

# SAT $\le_P$ 3SAT $\le_P$ SubsetSum $\equiv_p$ Partition

**Theorem. SAT $\le_P$ ILP $\le_P$ LP**

**Theorem. SAT $\le_P$ 3SAT**

**Theorem. 3SAT $\le_P$ SubsetSum**

**Theorem. SubsetSum $\le_P$ Partition**

**Theorem. Partition $\le_P$ SubsetSum (for fun)**

**Therefore, not only is SAT in NP–Complete, but so are ILP, LP, 3SAT, Partition, and SubsetSum.**


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# 3SAT $\leq_p$ SubsetSum

Assuming a **3SAT expression (a + ~b + c) (~a + b + ~c)**

| | a | b | c | a+~b+c | ~a+b+~c |
|---|---|---|---|---|---|
| a | 1 | 0 | 0 | 1 | 0 |
| ~a | 1 | 0 | 0 | 0 | 1 |
| b | 0 | 1 | 0 | 0 | 1 |
| ~b | 0 | 1 | 0 | 1 | 0 |
| c | 0 | 0 | 1 | 1 | 0 |
| ~c | 0 | 0 | 1 | 0 | 1 |
| C1 | 0 | 0 | 0 | 1 | 0 |
| C1’ | 0 | 0 | 0 | 1 | 0 |
| C2 | 0 | 0 | 0 | 0 | 1 |
| C2’ | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 3 | 3 |


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# SubsetSum Matrix

- One column per variable and one column per clause
- Two rows per variable (true/false so only one can be chosen per variable) and two rows per clause (optional pads to get to 3's in clause columns, provided we are already at least a 1).
- Each row is a number and summing them never results in carry to next column, so each column is independent of other and only influenced by rows we select.
- Goal of 1 … 1 3… 3 forces one choice (true or false per variable) and satisfiability for every clause (must have a 1 in at least one variable row of each clause column )

# How it works

- Satisfying (a + ~b + c) (~a + b + ~c)
- Make a, b and c true (satisfies)
  Rows a, b and c get us 11121
  Padding with C1, C2 and C2' gets 11133
- Make a, ~b and c true (does not satisfy)
  Rows a, ~b and c get us 11130
  No amount of padding can get the last column to be 3 (2 is max)


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# Partition

- Given a Multiset $S = \{s_1, s_2, \ldots, s_n\}$, where each $s_i$ is a positive integer, can we partition it into two sub-bags P1, P2 such that $P1 \cup P2 = S$ and $P1 \cap P2 = \emptyset$ ?
- Note: If S contains multiple copies of some integer, each is considered distinct and thus does not unduly influence the intersection and union operators above

# SubsetSum $\equiv_p$ Partition Details

- Partition is polynomial equivalent to SubsetSum
  - Let $i_1, i_2, .., i_n$ , G be an instance of SubsetSum. This instance has answer "yes" iff
    $i_1, i_2, .., i_n$ , 2*Sum($i_1, i_2, .., i_n$ ) – G,Sum($i_1, i_2, .., i_n$ ) + G
    has answer "yes" in Partition. Here we assume that G ≤ Sum($i_1, i_2, .., i_n$ ), for, if not, the answer is "no."
  - Let $i_1, i_2, .., i_n$ be an instance of Partition. This instance has answer "yes" iff
    $i_1, i_2, .., i_n$ , Sum($i_1, i_2, .., i_n$ )/2
    has answer "yes" in SubsetSum

# SubsetSum $\equiv_p$ Partition

- [(15, 17, 27, 11, 4, 12, 33, 5, 6, 21, 2), 57]
- A solution is 15, 17, 11, 12, 2
- Sum of all is 153
- Mapping to Partition is
  - (15, 17, 27, 11, 4, 12, 33, 5, 6, 21, 2, 306-57, 153+57)
  - (15, 17, 27, 11, 4, 12, 33, 5, 6, 21, 2, 249, 210)
  - (15+17+11+12+2+249) = 306
  - (27+4+33+5+6+21+210) = 306
- Going other direction map above to
  - [(15, 17, 27, 11, 4, 12, 33, 5, 6, 21, 2, 249, 210), 306]

# VERTEX COVERING (VC) DECISION PROBLEM IS NP-HARD


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# 3SAT to Vertex Cover

- Vertex cover seeks a set of vertices that cover every edge in some graph
- Let $I_{3\text{-}SAT}$ be an arbitrary instance of 3-SAT. For integers n and m, $U = \{u_1, u_2, \ldots, u_n\}$ and $C_i = \{z_{i1}, z_{i2}, z_{i3}\}$ for $1 \le i \le m$, where each $z_{ij}$ is either a $u_k$ or $u_k'$ for some k.
- Construct an instance of VC as follows.
- For each i, $1 \le i \le n$, construct two vertices, $u_i$ and $u_i'$ with an edge between them.
- For each clause $C_i = \{z_{i1}, z_{i2}, z_{i3}\}$, $1 \le i \le m$, construct three vertices $z_{i1}$, $z_{i2}$, and $z_{i3}$ and form a "triangle on them. Each $z_{ij}$ is one of the Boolean variables $u_k$ or its complement $u_k'$. Draw an edge between $z_{ij}$ and the Boolean variable (whichever it is). Each $z_{ij}$ has degree 3. Finally, set k = n+2m.
- Theorem. The given instance of 3-SAT is satisfiable if and only if the constructed instance of VC has a vertex cover with at most k vertices.

# VC Variable Gadget

To cover the edge in between x and ~x, at least one of these must be chosen


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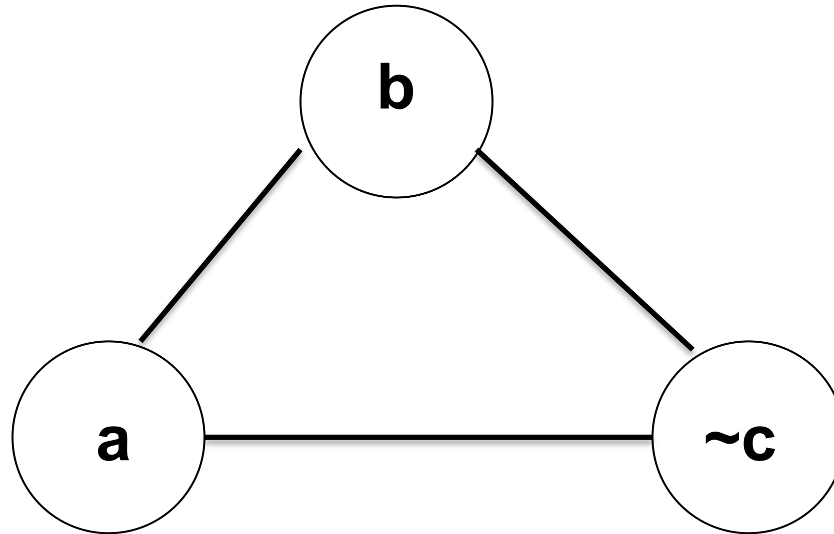
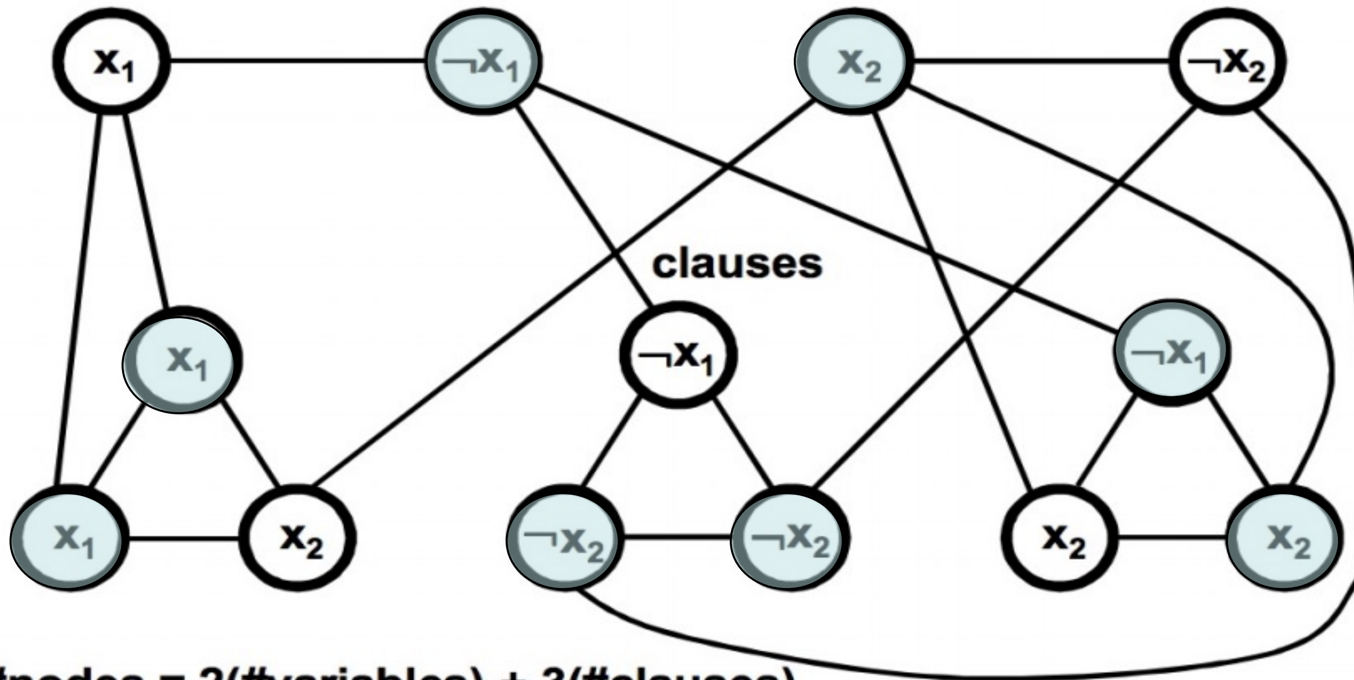
# VC Clause Gadget




**a + b + ~c**

To cover the edges here, at least two of three vertices must be chosen

# VC Gadgets Combined




Goal is to cover all variables (really edges) with **v + 2c** nodes (minimum needed); **v**=#variables; **c** = #clauses; for above that is 2 + 2*3 = 8: Light blue are choices

# Why VC Gadgets Work

- For each variable gadget, we must either choose the variable or its complement to cover the edge connecting them; Choosing both is wasteful
- For each clause gadget, we must cover its internal edges. This requires 2 per clause, but also need to cover all edges entering from variable gadgets, if not already covered by the selection of the corresponding variable gadget
- If we can cover all edges, with just v+2c nodes then we have attained the minimum possible and guaranteed that each clause has at least one of its literals true. This allows the corresponding variable selection (true/false) to cover the incoming edge allowing the three internal edges to be covered by the other two variable nodes in the clause. If more than one literal is covered, you have a choice of which covered internal node to not choose for the clause gadget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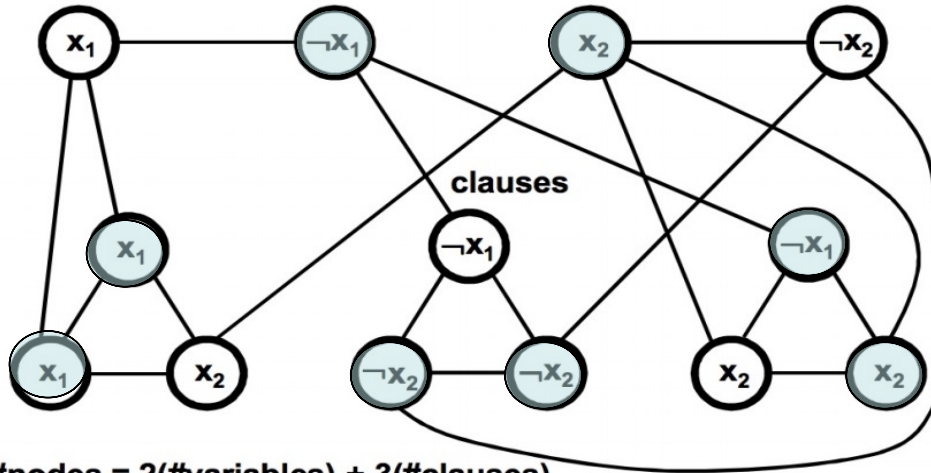
# Explaining Example




Solution choses ~x1, x2; By choosing those variable gadget nodes we cover both variable gadgets. We know we must cover all clause gadgets and the edges entering them from the variable gadgets. For the first clause, we do not need to cover the edge entering from variable gadget x2, but we must cover the other two external edges and the three internal edges. Choosing the two x1 nodes in clause 1 covers all external and internal edges. Had we chosen ~x1 in the x1 variable gadget and ~x2 in the x2 variable gadget we would have had to chose x2 in the first clause gadget thereby exceeding our quota of v + 2c. I leave it to you to see why the others work and to understand why we had no actual constraints in the third clause gadget (any two would have worked).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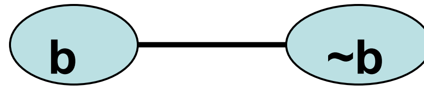
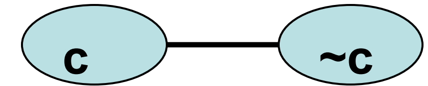
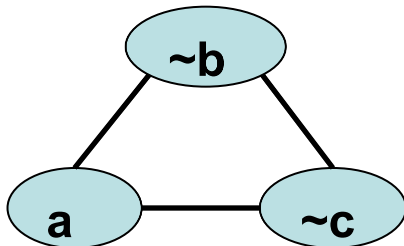
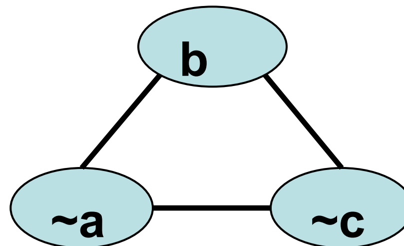
# VC Just the Gadgets

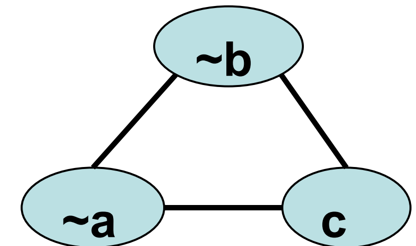
**(a,~b,~c)(~a,b,~c)(~a,~b,c)**










**Requires |V| + 2*|C|**
**Trivial to reach goal if no other edges**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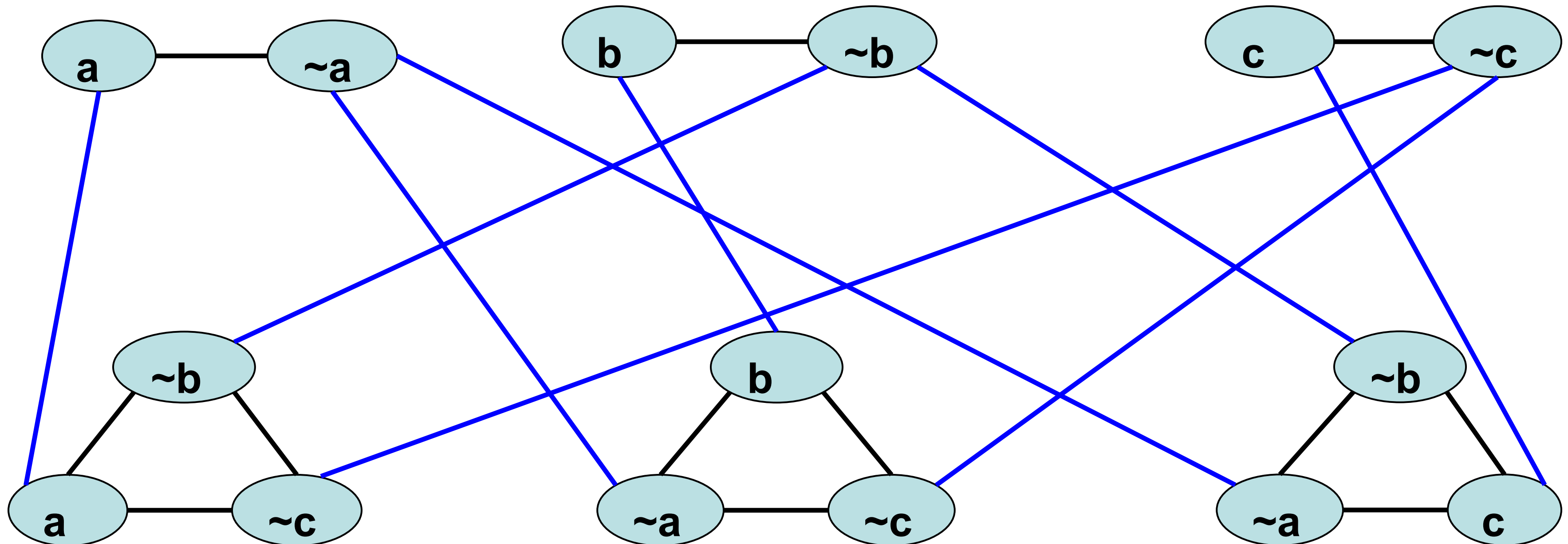
# VC + Variable/Clause Edges




**GOAL = 3 + 3*2 = 9**

**The choice of variable assignments influences which nodes in clauses must be chosen to cover external edges**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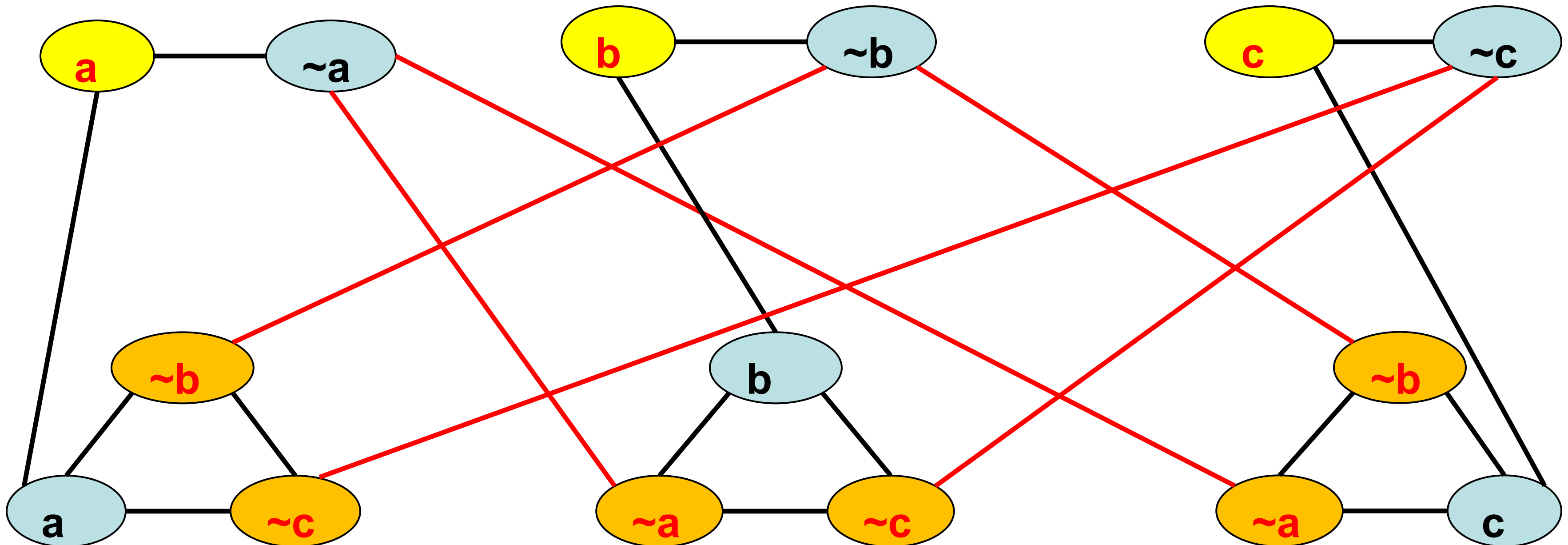
# VC with Forced Solution

(a,~b,~c)(~a,b,~c)(~a,~b,c)




**GOAL = 3 + 3*2 = 9**
**Assignment is a, b, c**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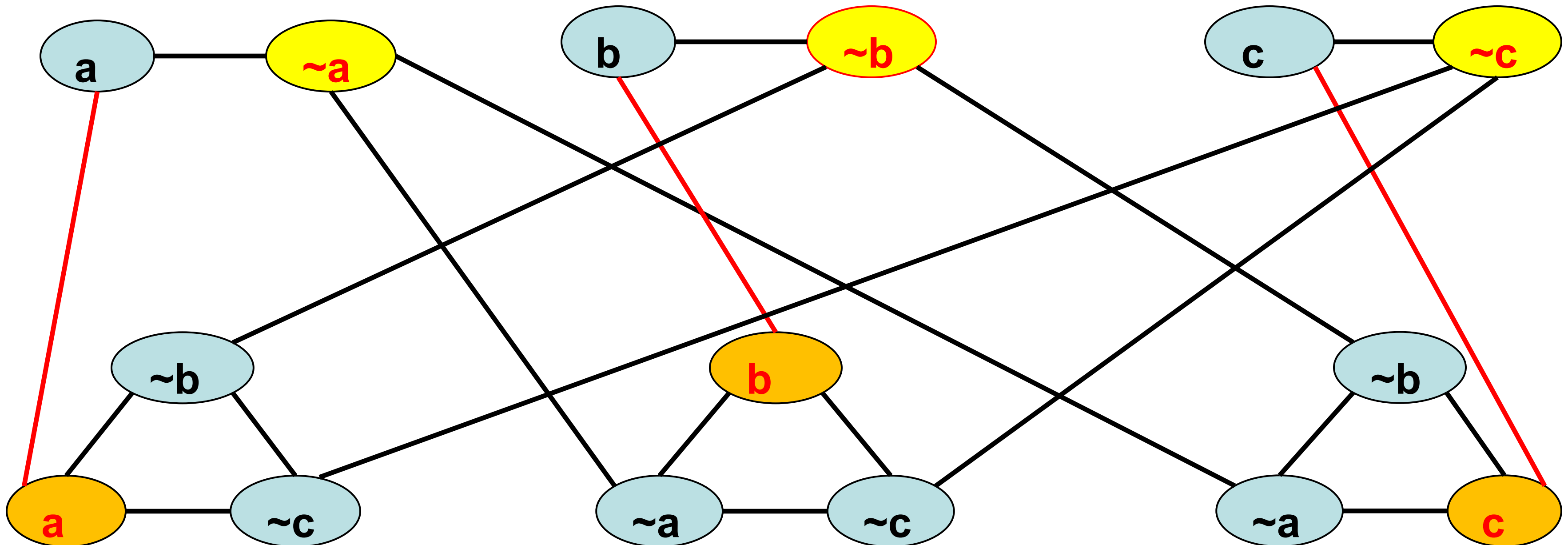
# VC Partially Forced Soln

**(a,~b,~c)(~a,b,~c)(~a,~b,c)**




**GOAL = 3 + 3*2 = 9**
**Assignment is ~a, ~b, ~c**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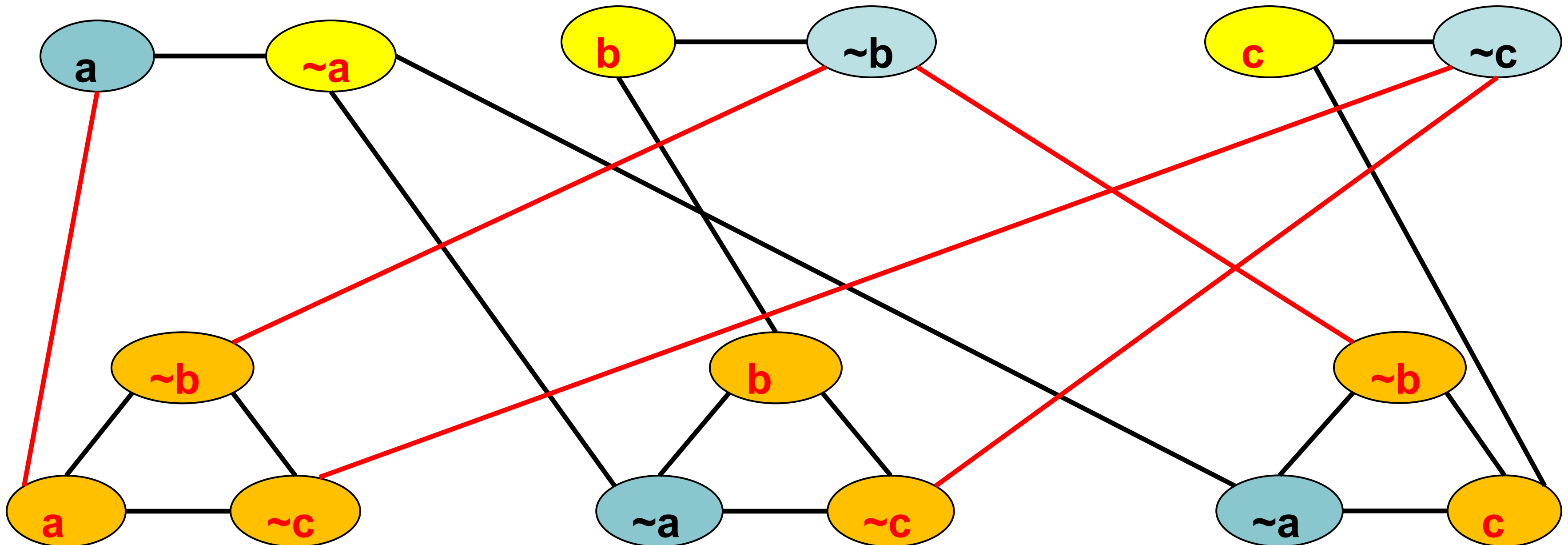
# VC Ex#2 Bad Assign

**(a,~b,~c)(~a,b,~c)(~a,~b,c)**




**GOAL = 3 + 3*2 = 9**
**Assignment is ~a, b, c**
**FAIL!!!**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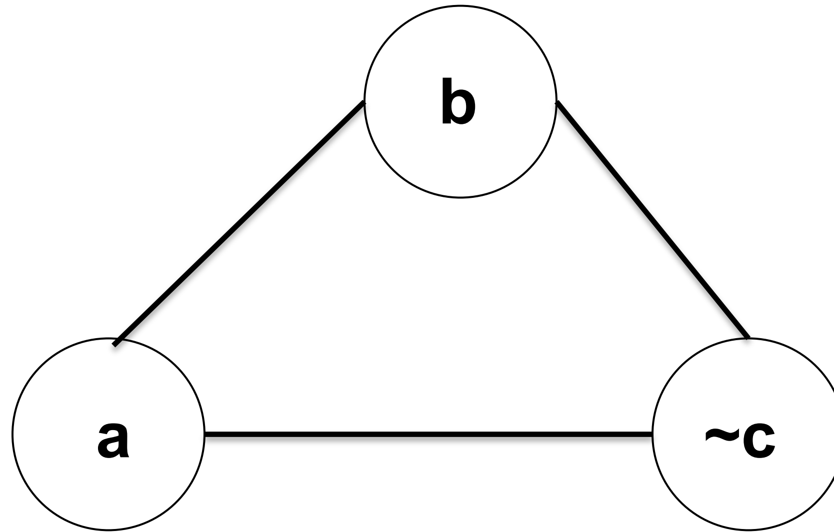
# Independent Set

- Independent Set
  - Given Graph G = (V, E), a subset S of the vertices is independent if there are no edges between vertices in S
  - The k-IS problem is to determine for a k>0 and a graph G, whether G has an independent set of k nodes
- Note there is a related NP-Hard optimization problem to find a Maximum Independent Set. It is even hard to approximate a solution to the Maximum Independent Set Problem.

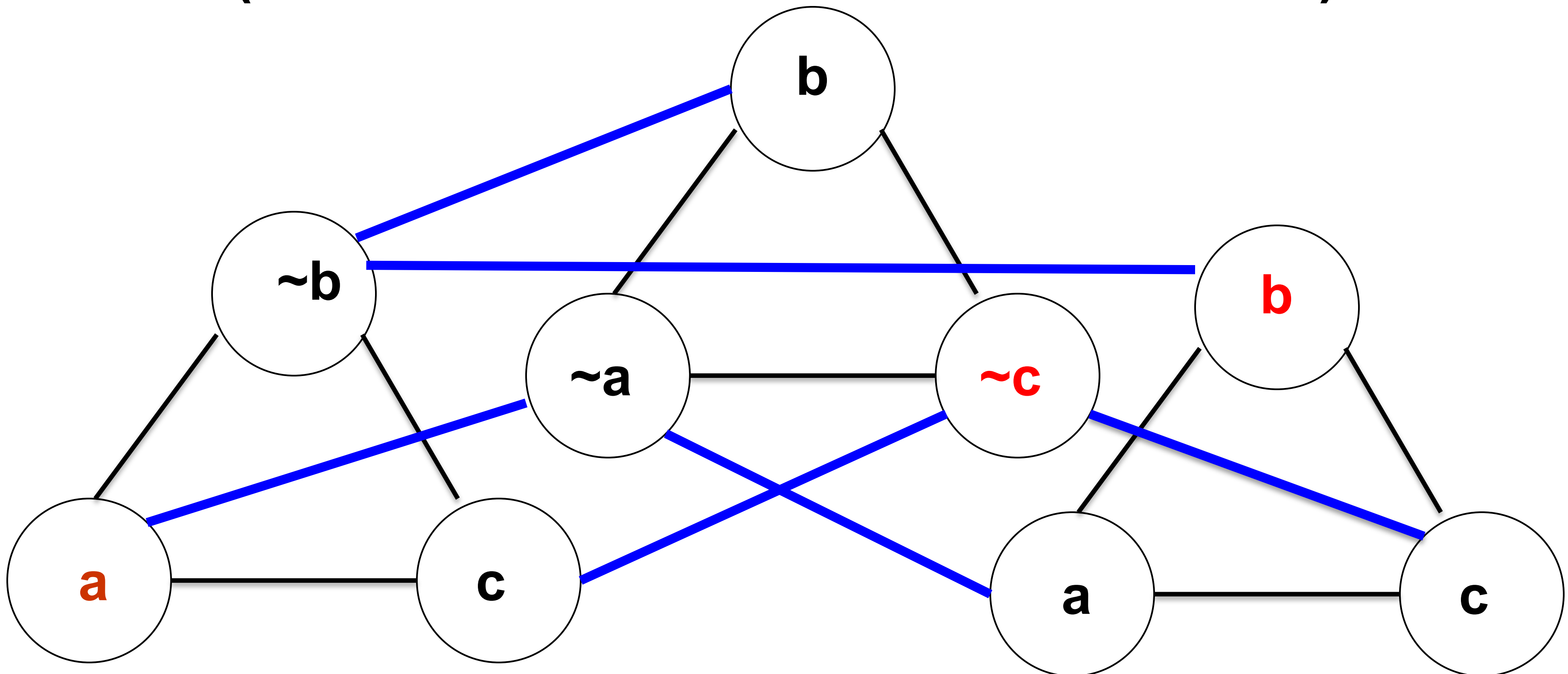
# IS (VC) Clause Gadget



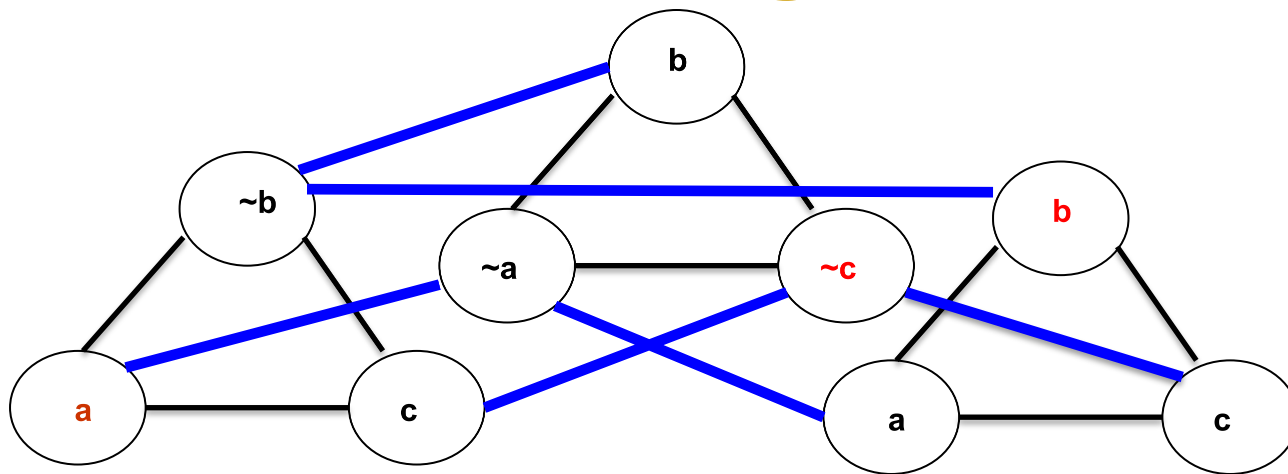

**a + b + ~c**

# 3SAT to IS

(a + ~b + c) (~a + b + ~c)(a + b + c), k=3
(k=number of clauses, not variables)



# Explaining the example




In each clause gadget we can only chose one node, else we would be choosing two nodes with a shared edge. Assume we select a in clause 1, we cannot choose ~a in any other clause as they have a shared edge. After choosing a in clause 1, we could choose either b or ~c in clause 2. Assume we select ~c in clause 2, we cannot choose c in any other clause as they have a shared edge. To reach three (the number of clauses, we need a choice left for clause 3. Fortunately, we have two choices, either a or b (I chose b in this case).

# K-COLOR (KC) DECISION PROBLEM IS NP-HARD

# K-Coloring

Given:

A graph G = (V, E) and an integer k.

Question:

Can the vertices of G be assigned colors from a palette of size k, so that adjacent vertices have different colors and use at most k colors?

3Coloring (3C) uses k=3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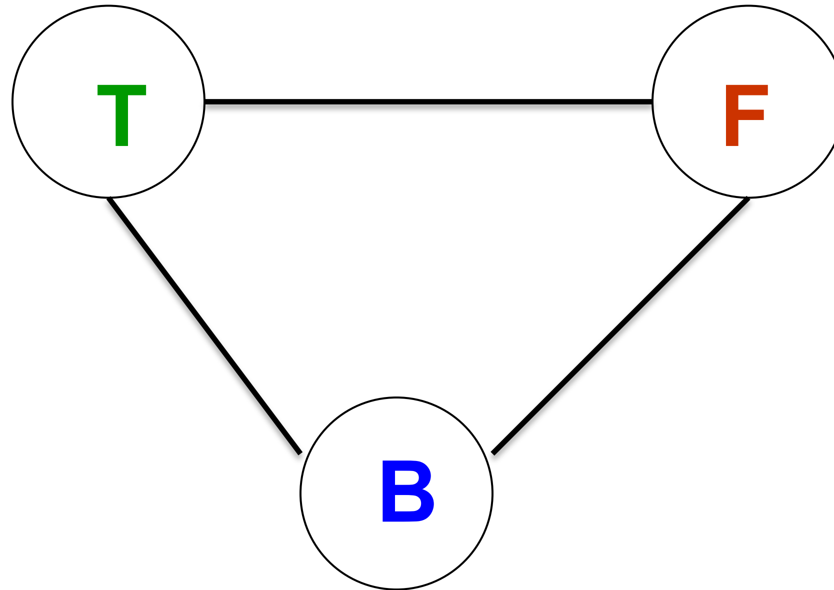
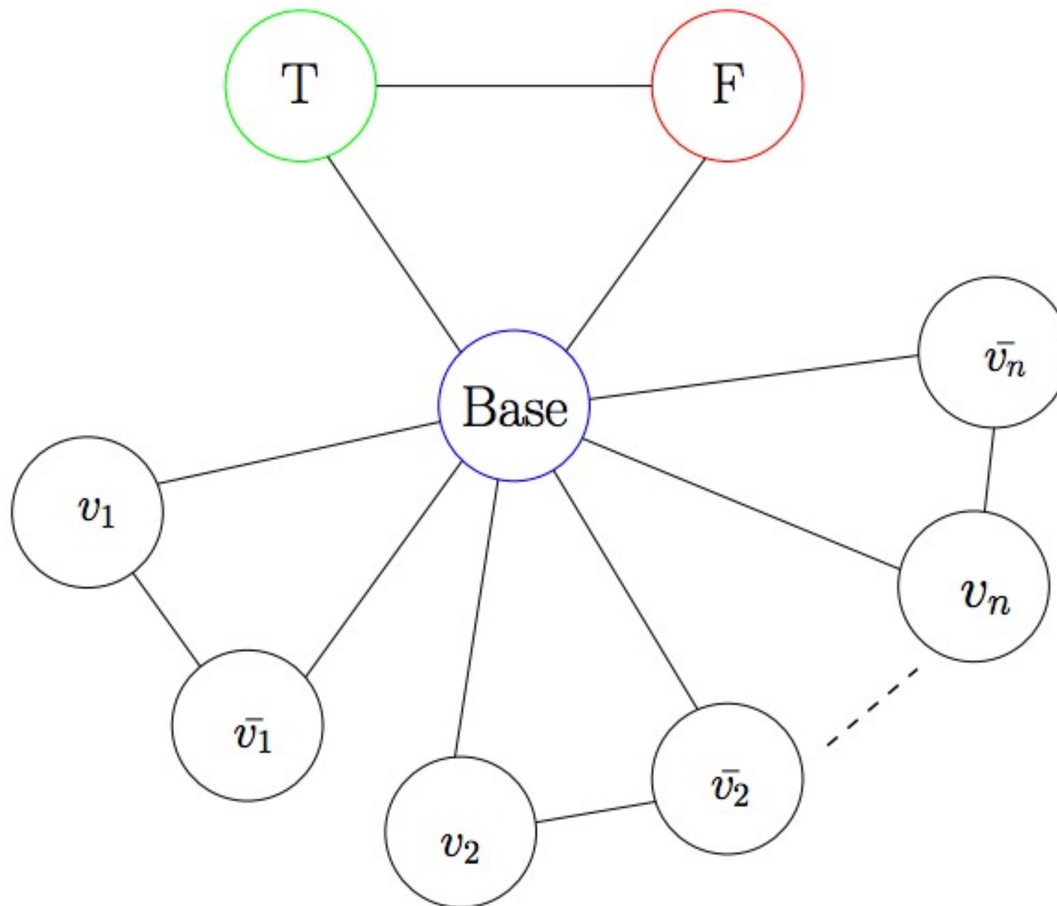
# 3C Super Gadget



# 3C Super + Variables Gadget





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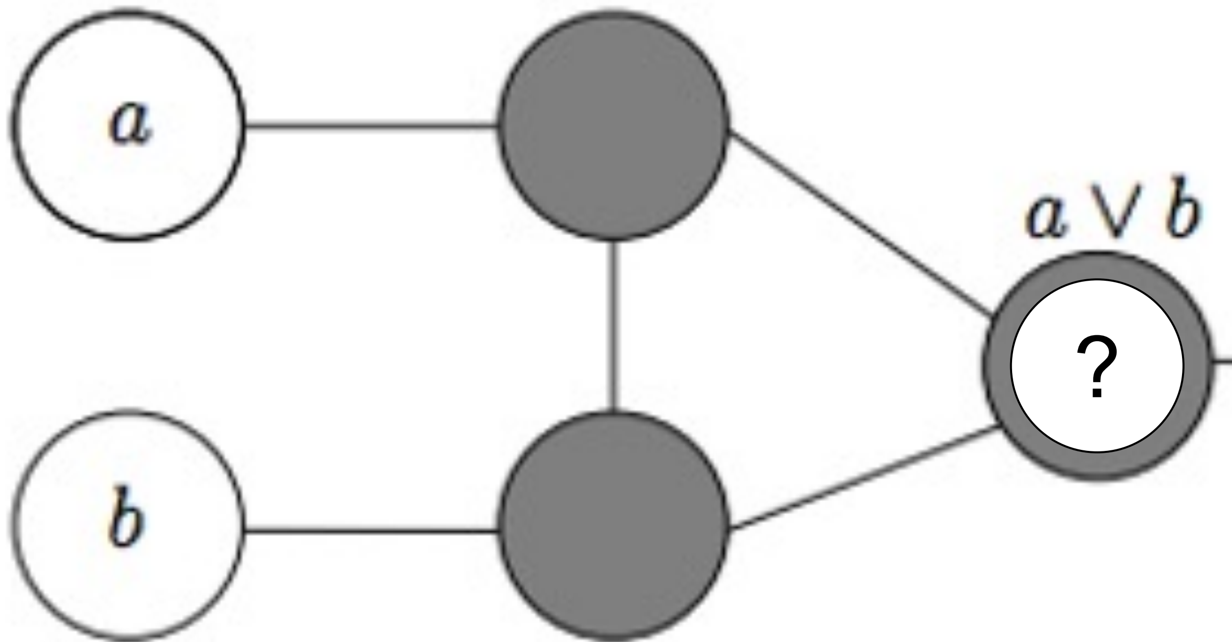
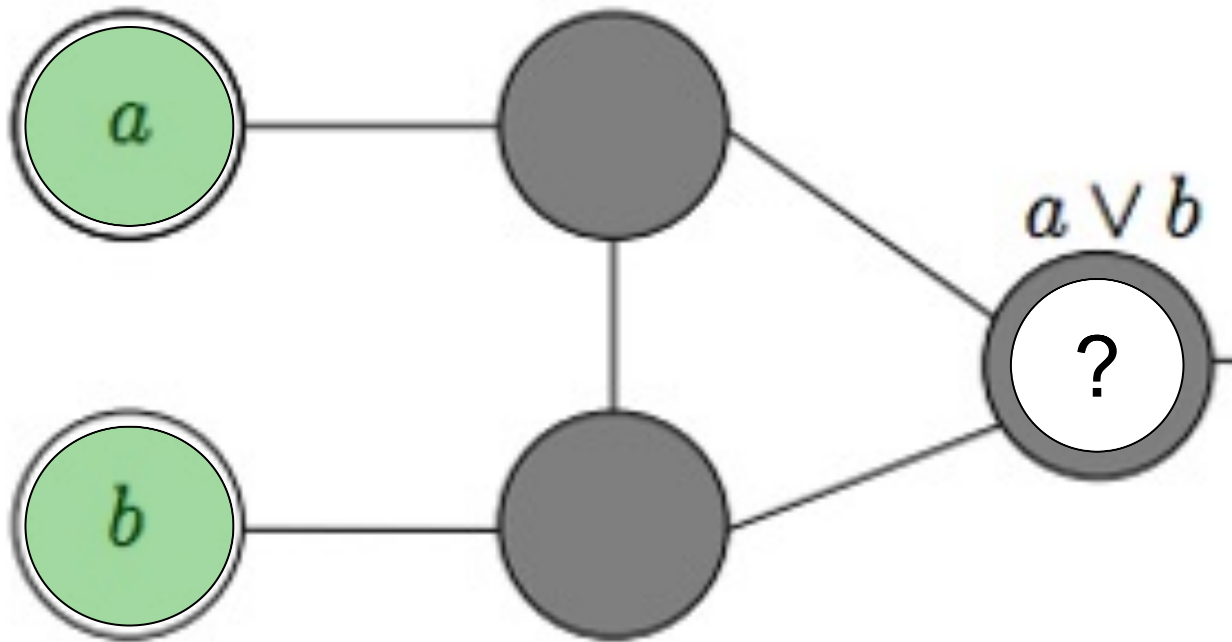
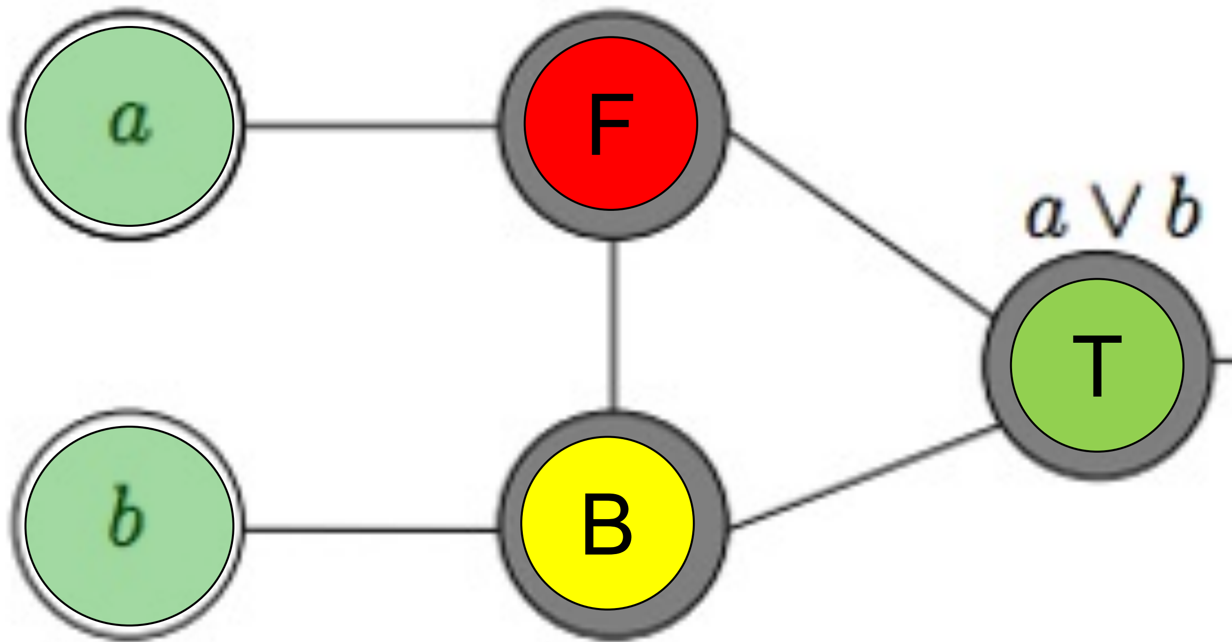
# A Simple OR Gadget



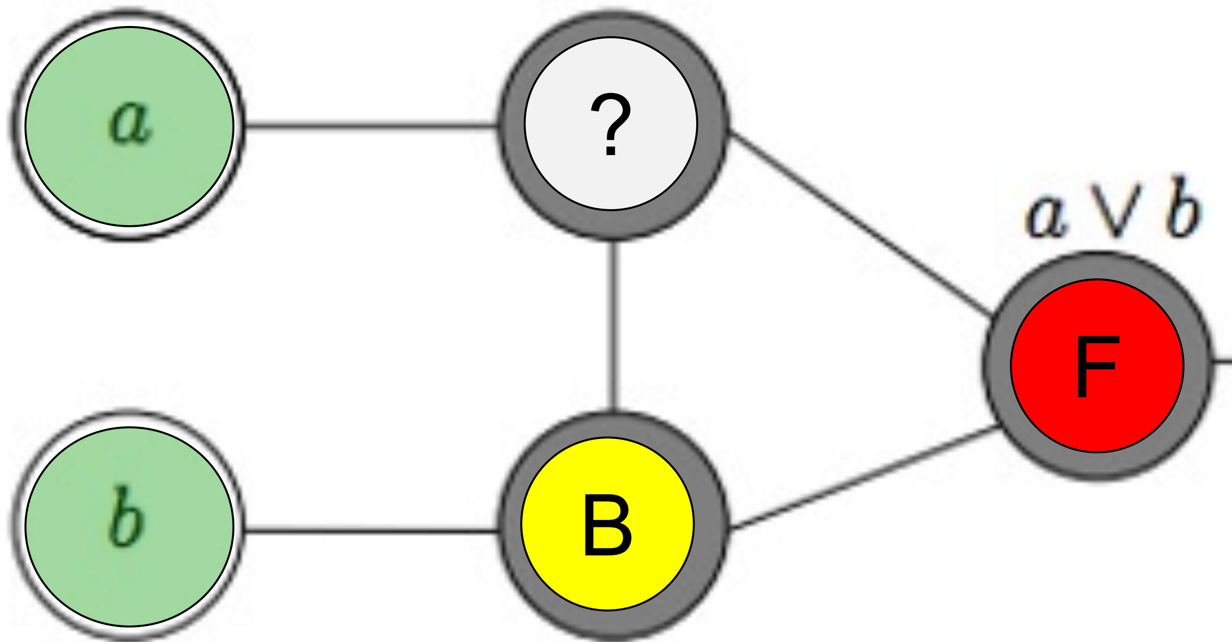
# What if a, b?



# What if a, b, T?



# What if a, b, F?





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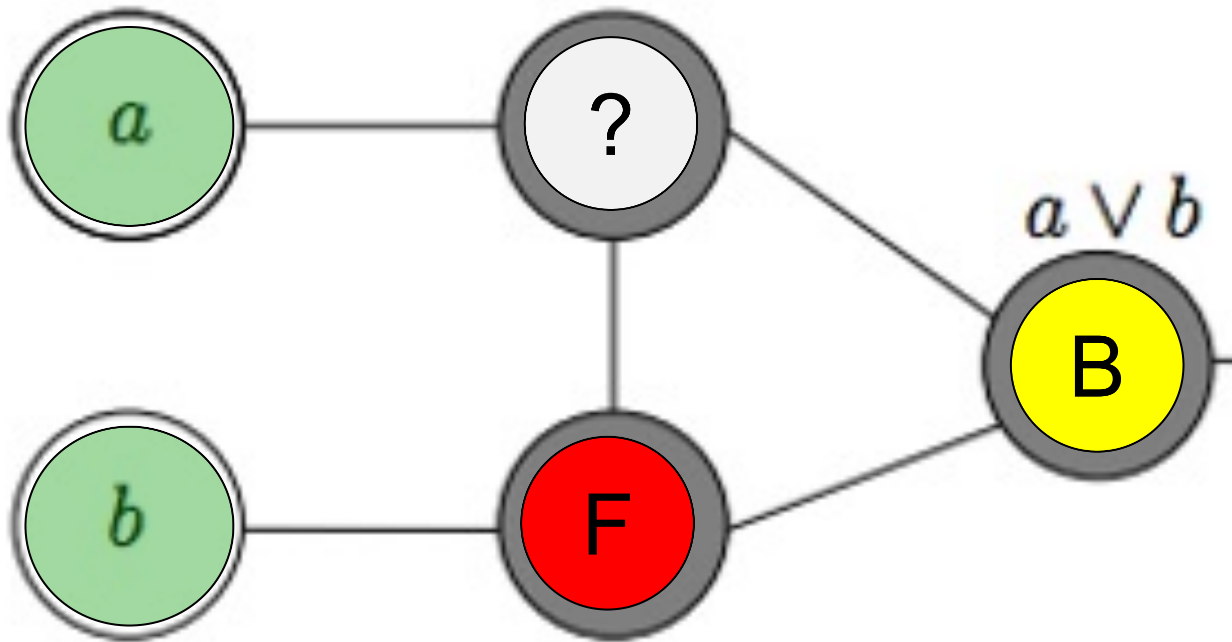
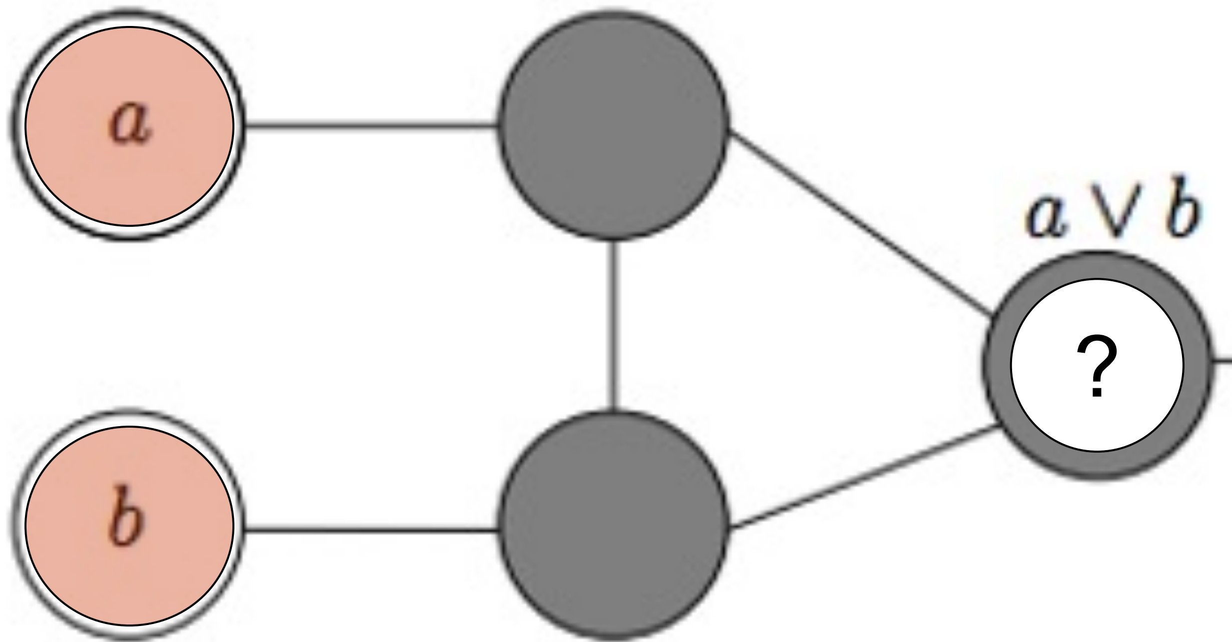
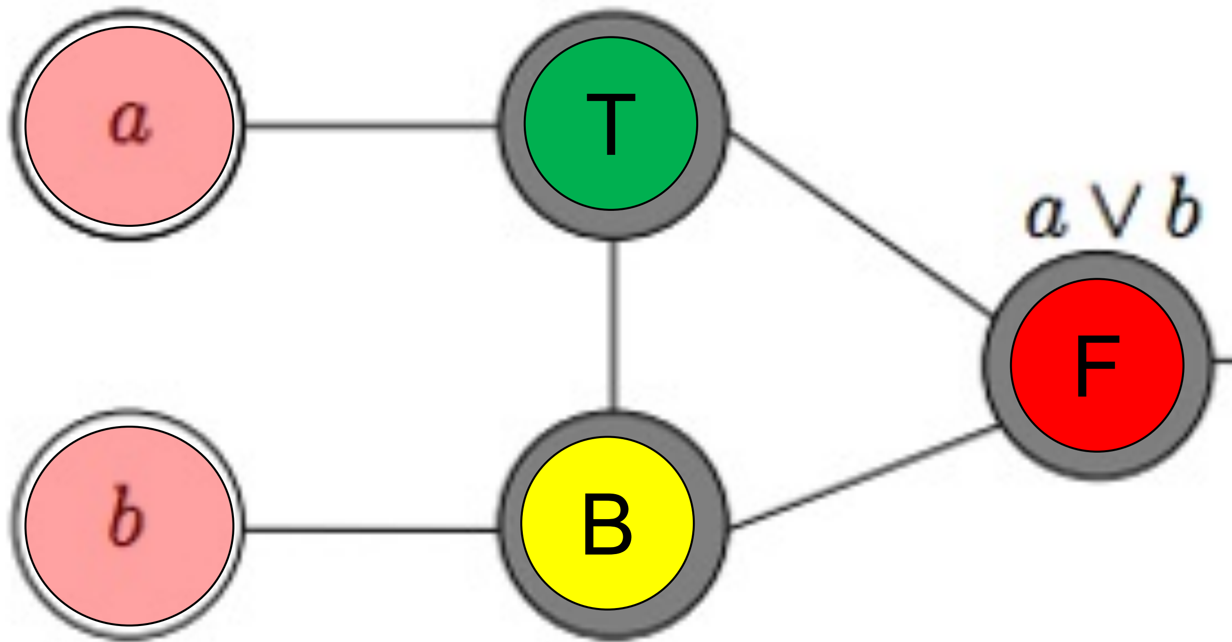
# What if a, b, B?



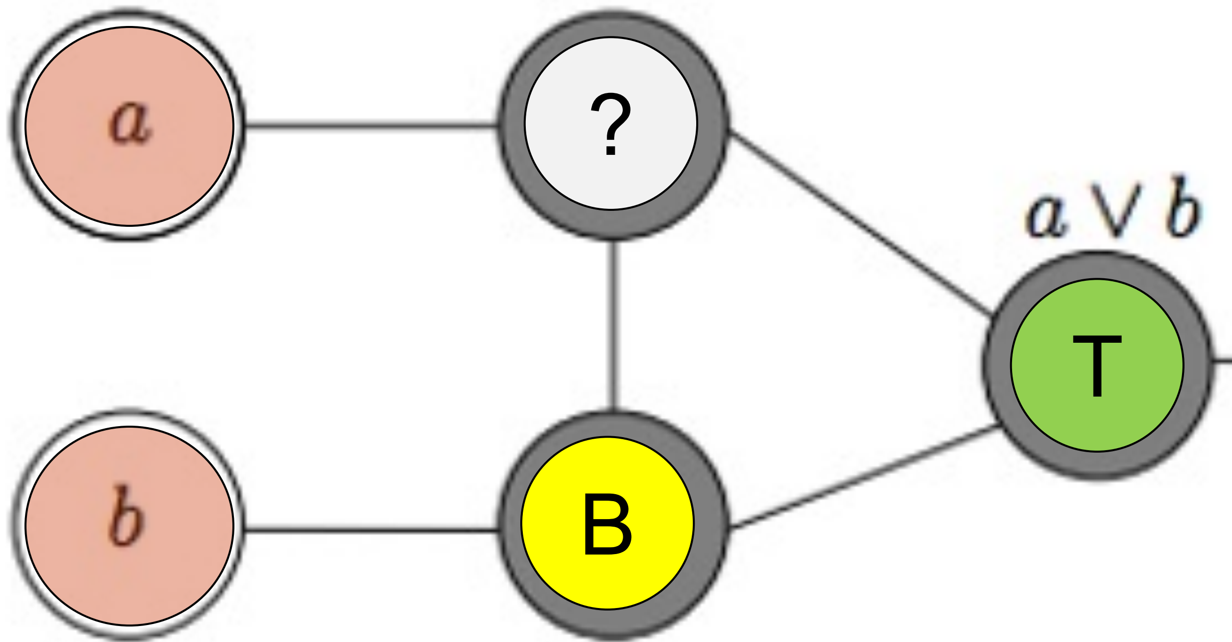
# What if ~a, ~b?



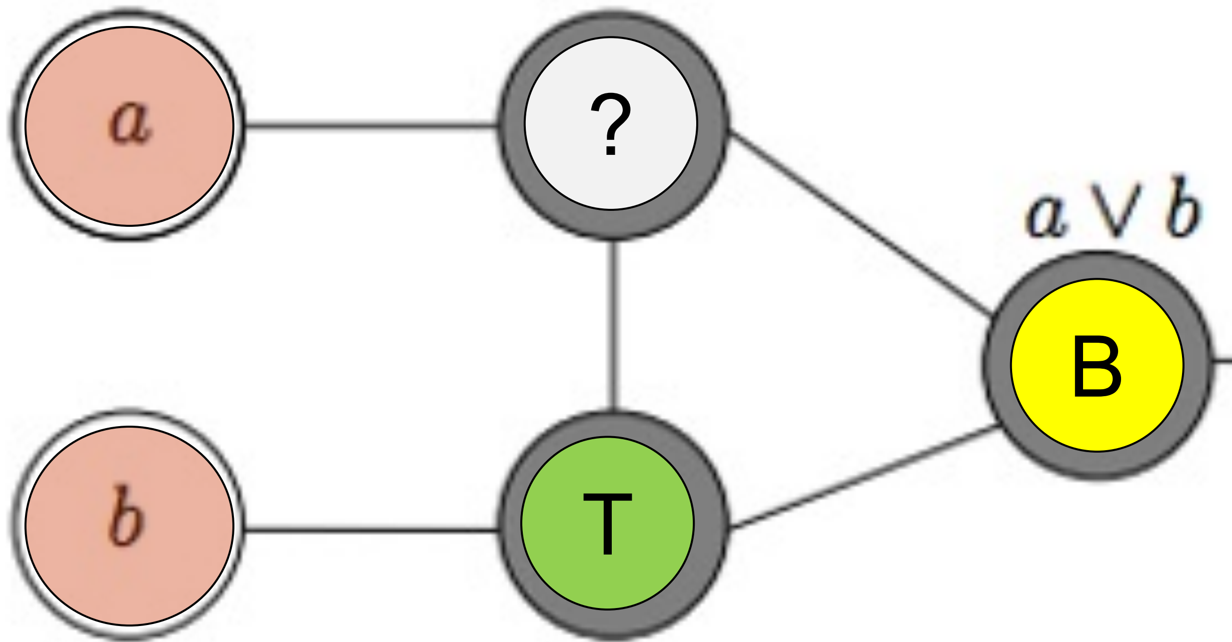
# What if ~a, ~b, F?



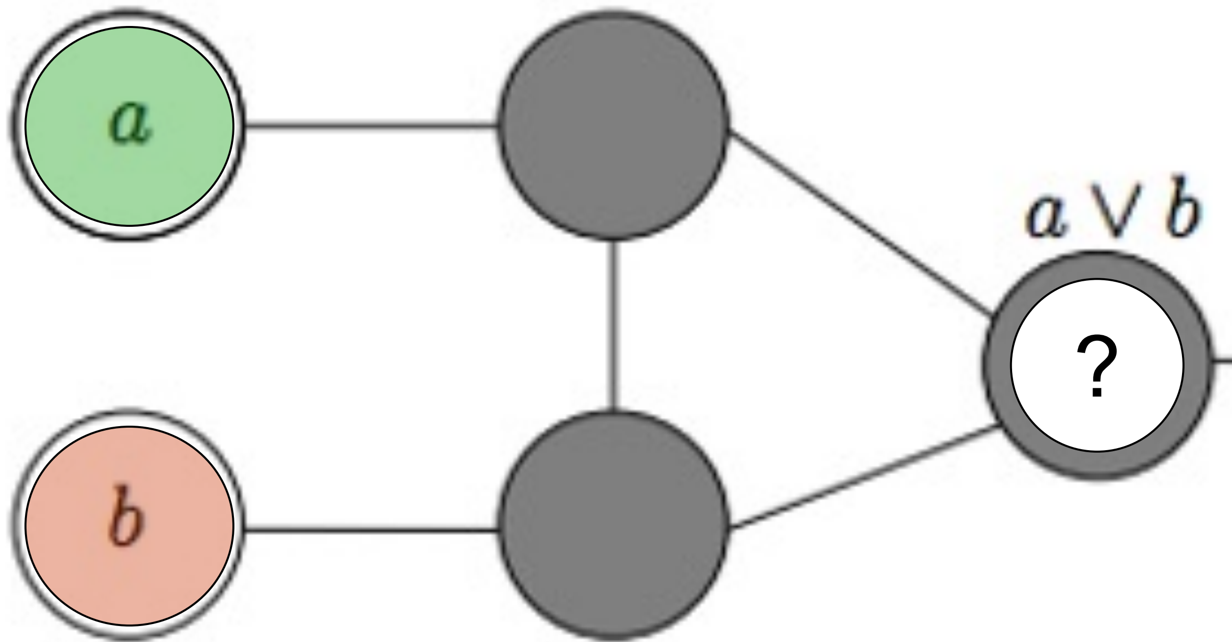
# What if ~a, ~b, T?



# What if ~a, ~b, B?



# What if a, ~b?





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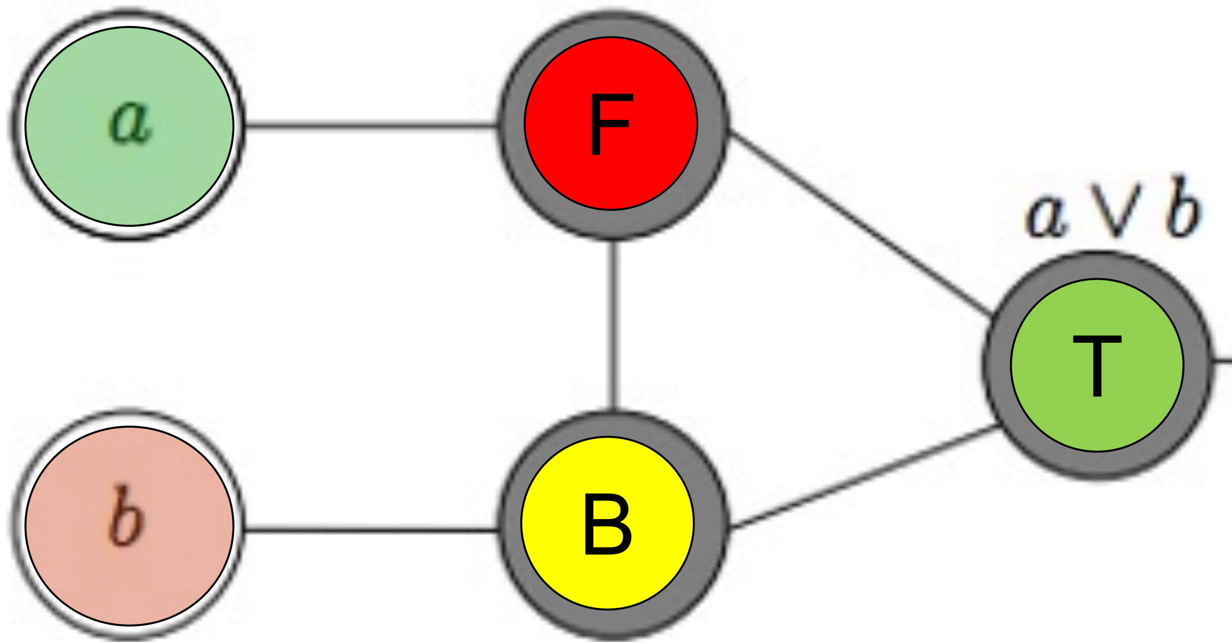
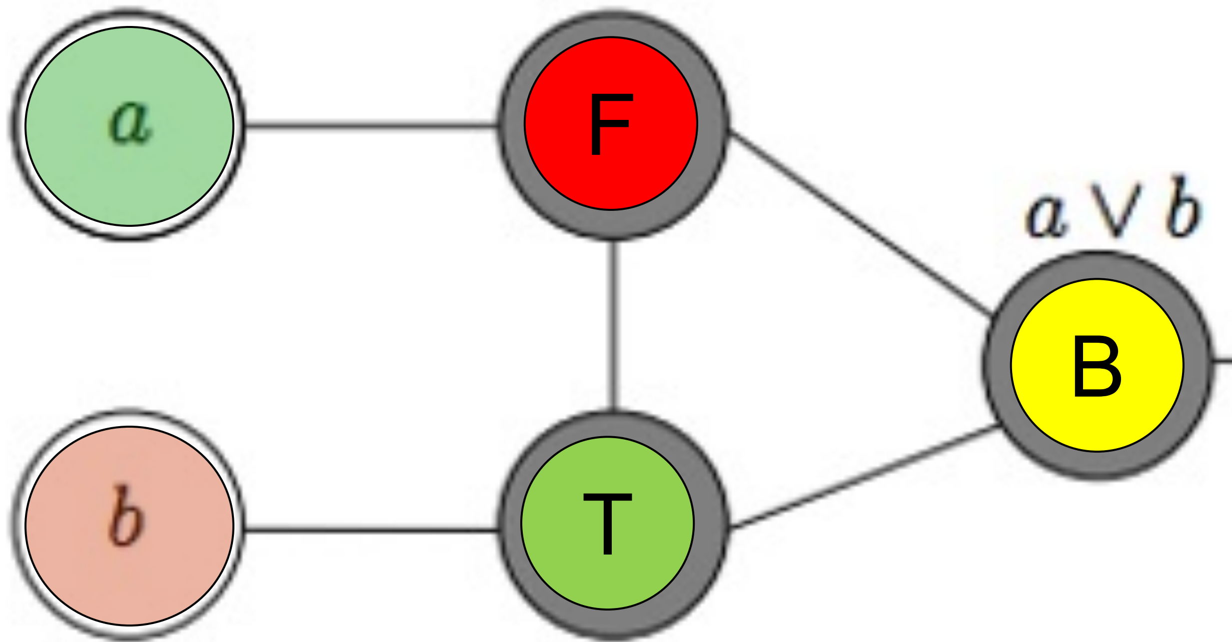
# What if a, ~b, T?



# What if a, ~b, B?





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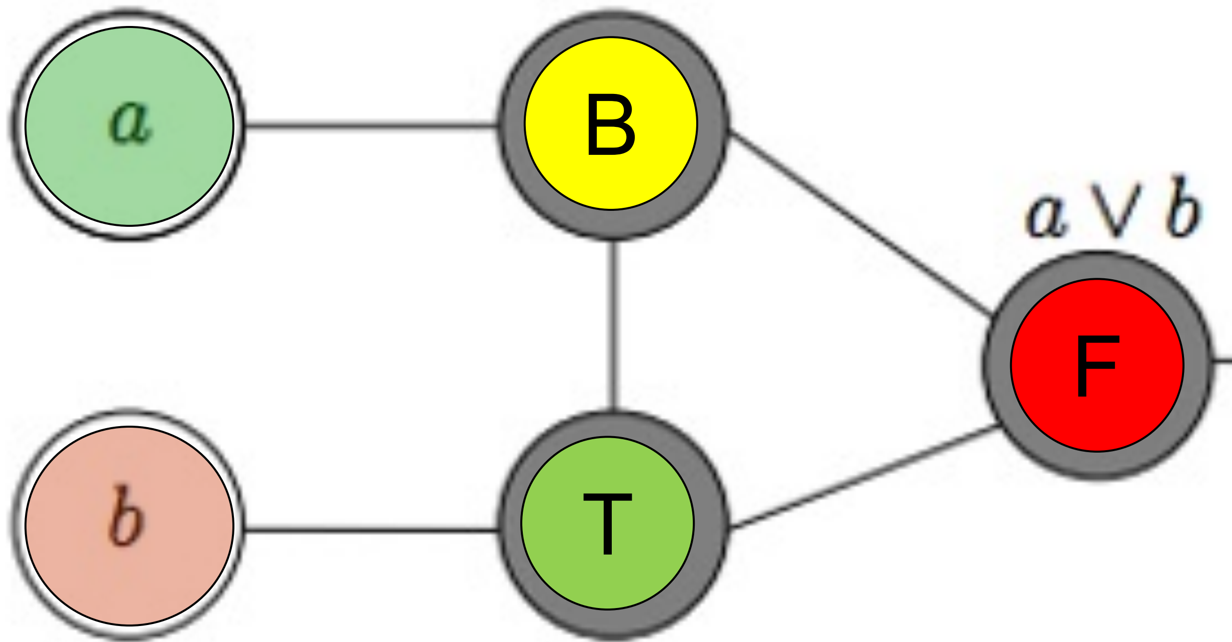
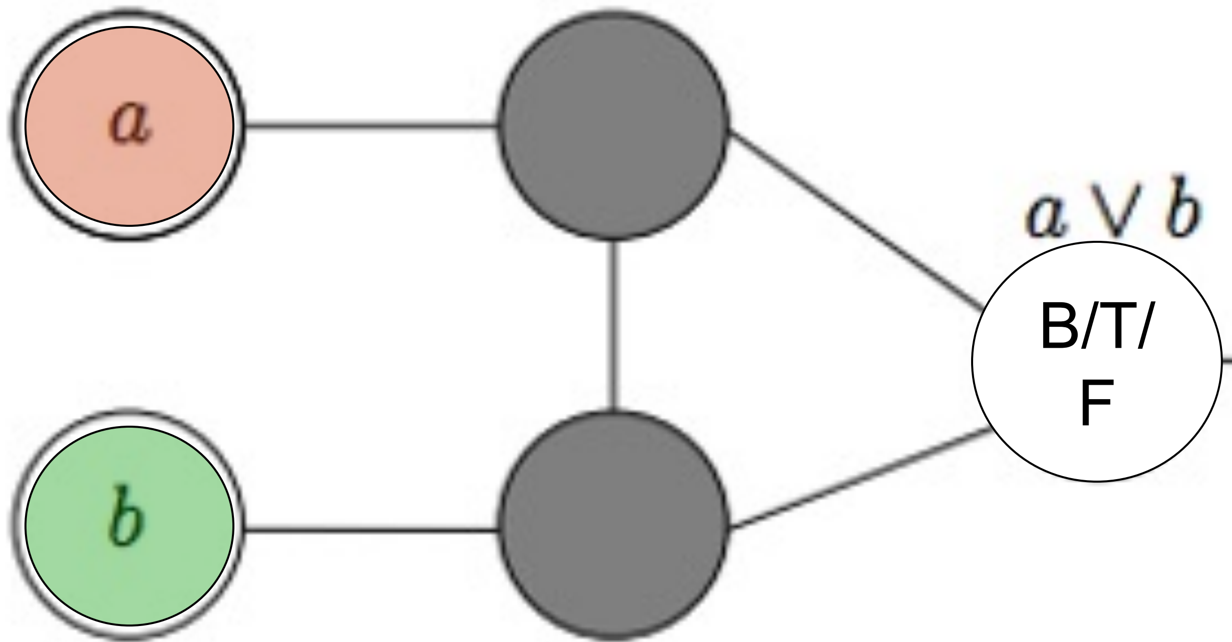
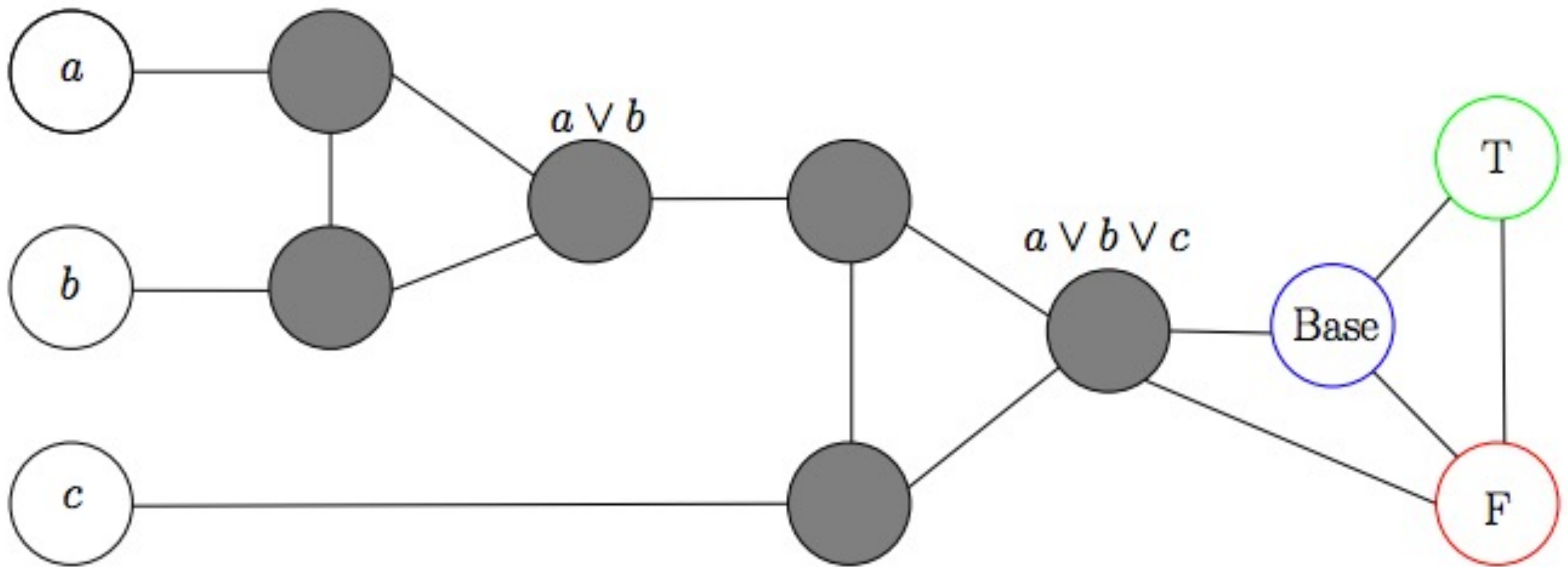
# What if a, ~b, F?



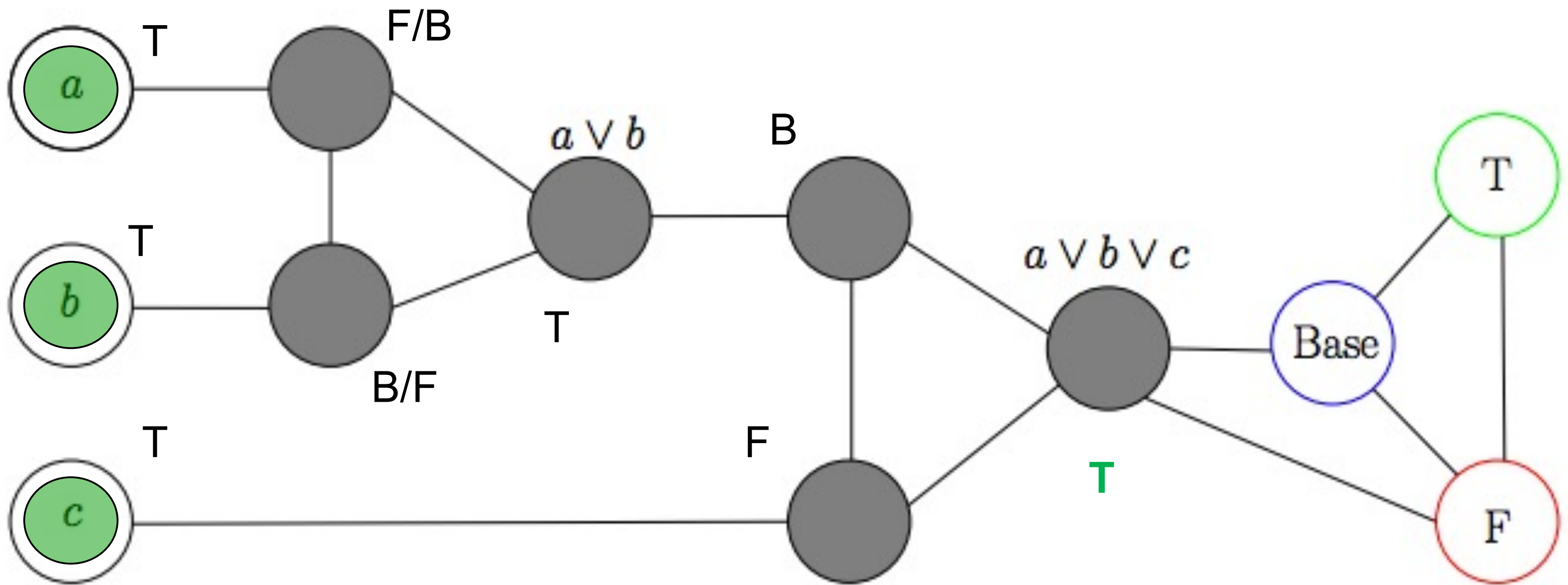
# What if ~a, b? same as a, ~b



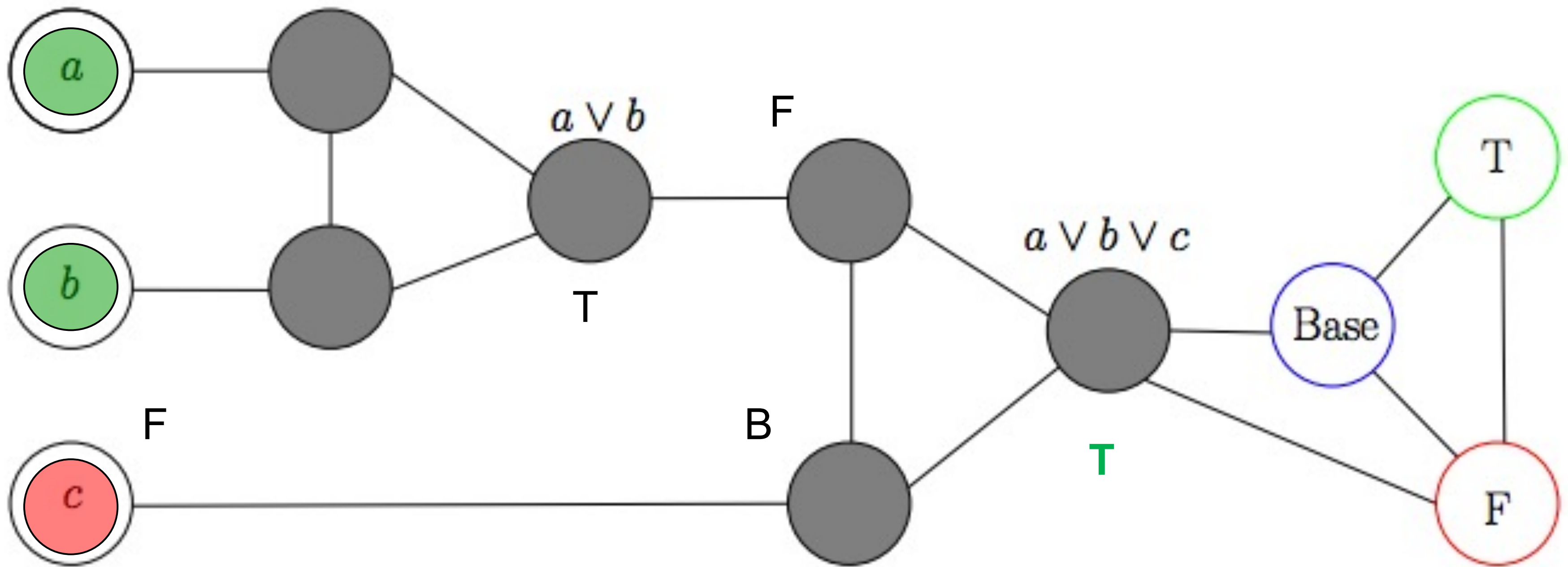
# 3C Clause Gadget



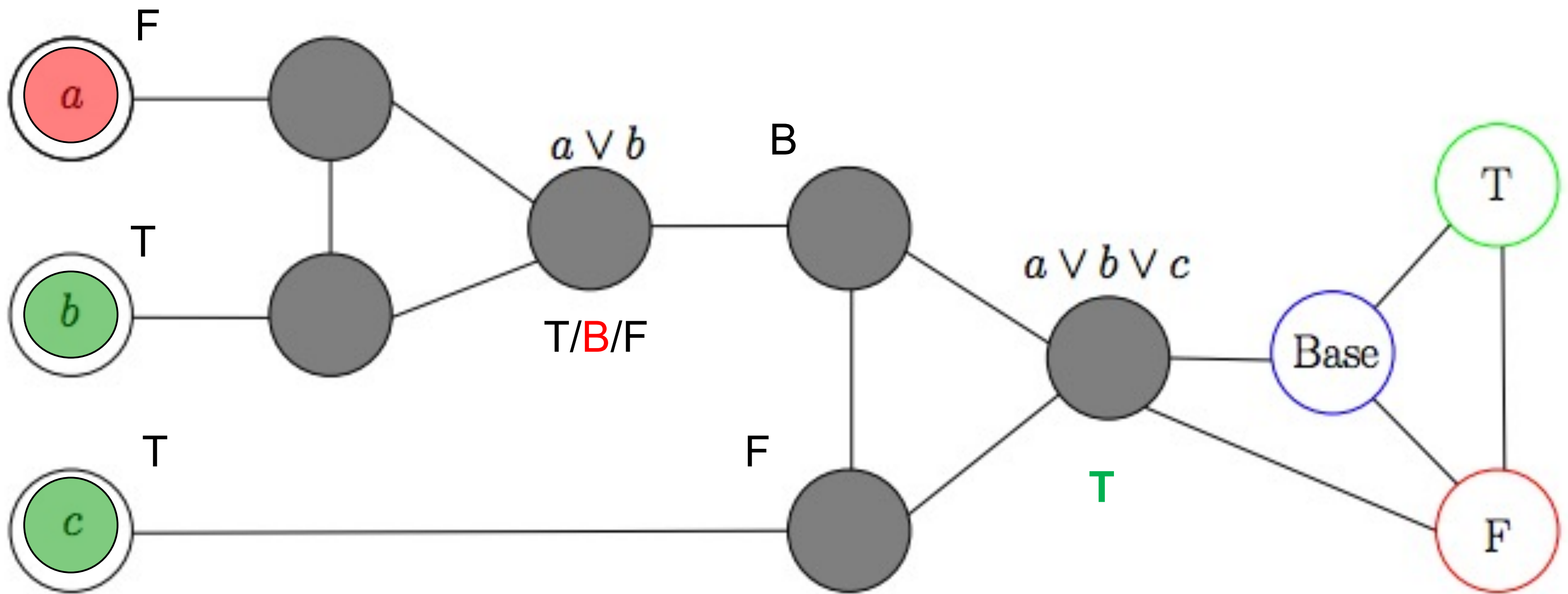
# Consider a, b, c



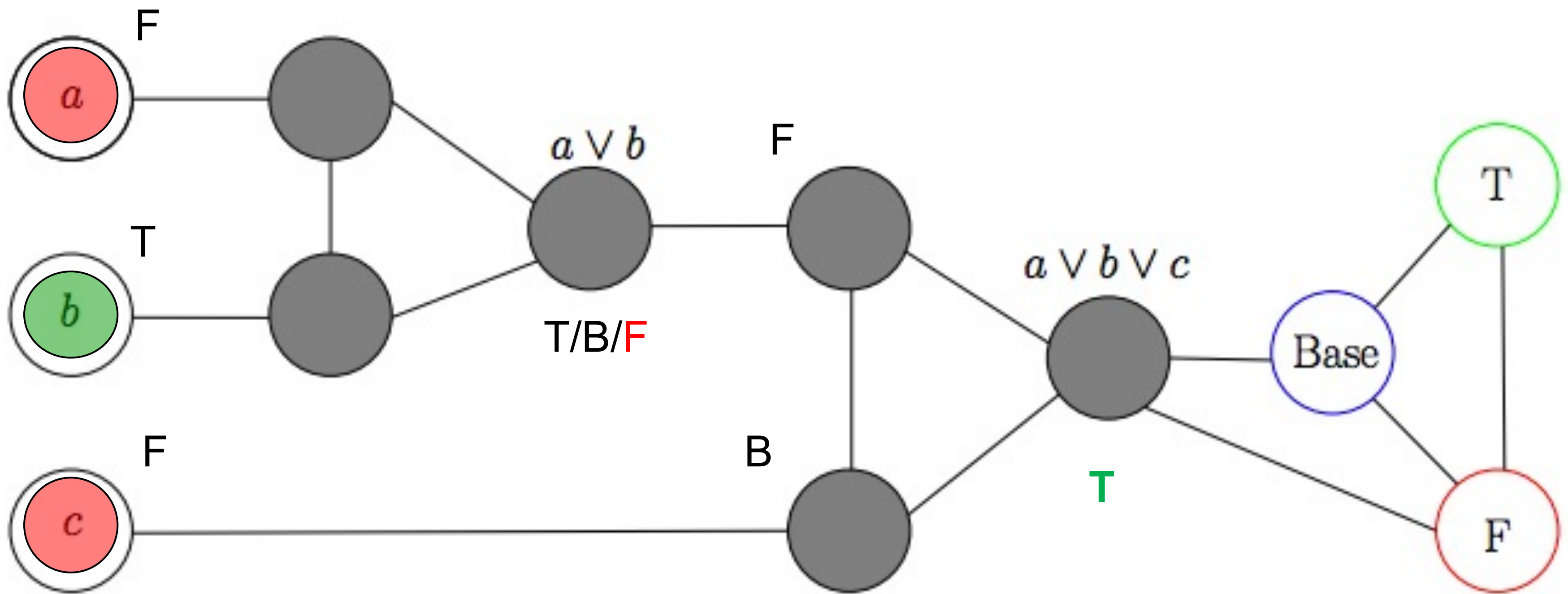
# Consider a, b, ~c



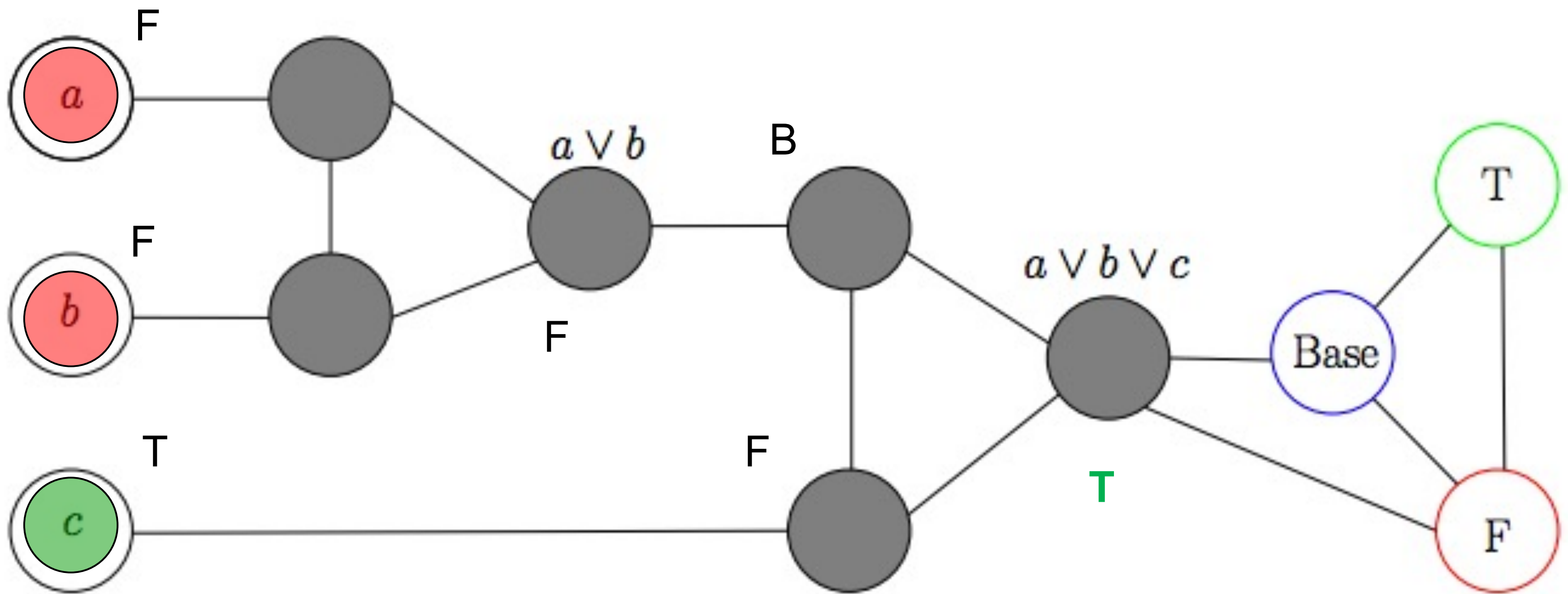
# Consider ~a, b, c or a, ~b, c



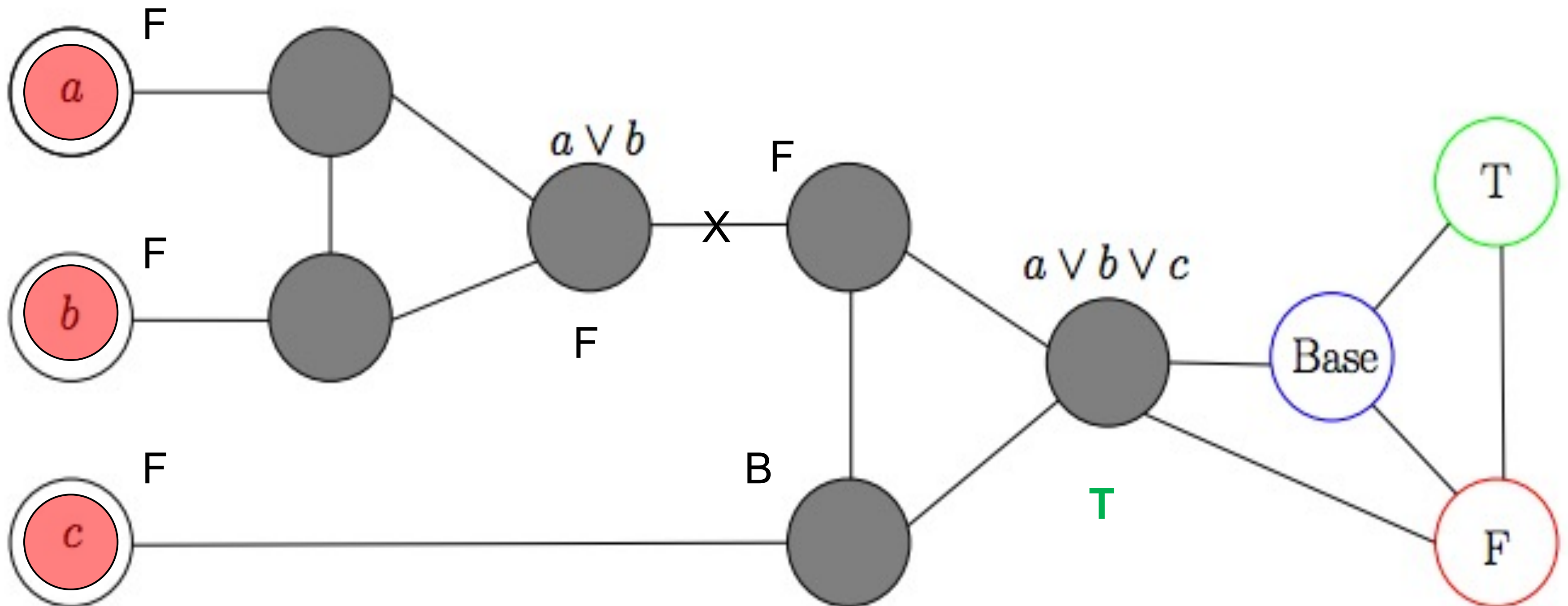
# Consider ~a, b, ~c or a, ~b, ~c



# Consider ~a, ~b, c



# Consider ~a, ~b, ~c





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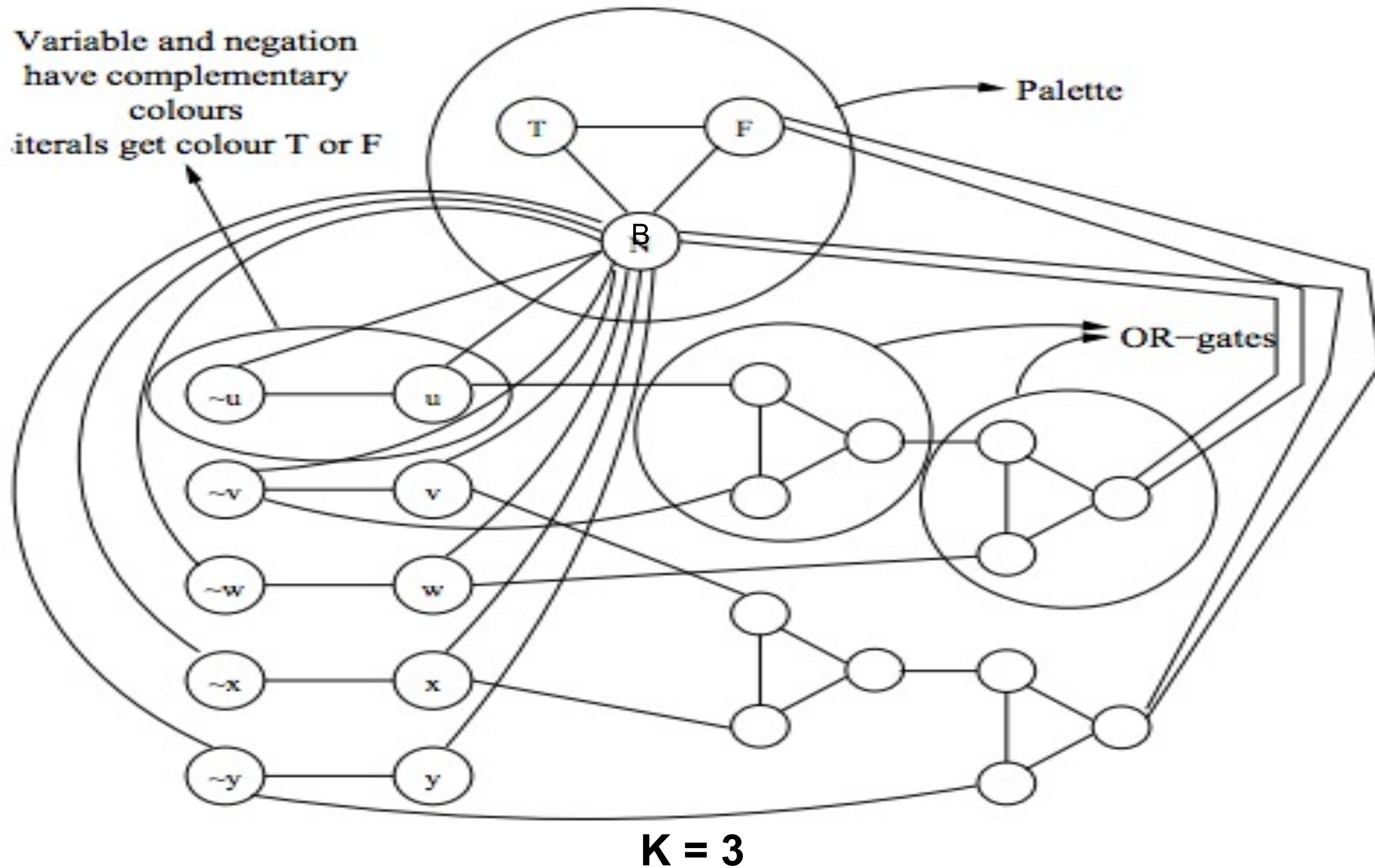
# KC Gadgets Combined

**(u + ~v + w) (v + x + ~y)**




**K = 3**



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# Register Allocation

- **Liveness: A variable is live if its current assignment may be used at some future point in a program's flow**
- **Optimizers often try to keep live variables in registers**
- **If two variables are simultaneously live, they need to be kept in separate registers**
- **Consider the K-coloring problem (can the nodes of a graph be colored with at most K colors under the constraint that adjacent nodes must have different colors?)**
- **Register Allocation reduces to K-coloring by mapping each variable to a node and inserting an edge between variables that are simultaneously live**
- **K-coloring reduces to Register Allocation by interpreting nodes as variables and edges as indicating concurrent liveness**
- **This is a simple mapping because it's an isomorphism**


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# Live Variable Analysis

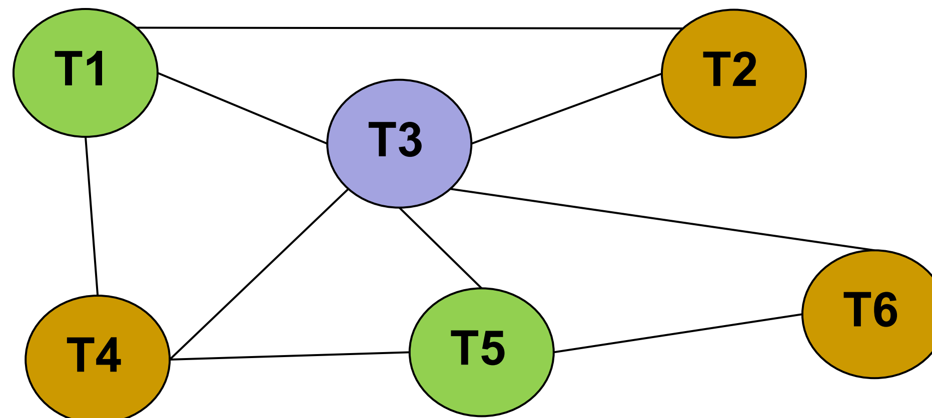
## Code

```
a = 1;
b = 2;
c = a * b;
d = a + 3;
e = c * 2;
f  = e / c;
Print e, f;
```

Minimum colors are 3 so need 3 registers to avoid spilling to memory and reloading

## No Optimization

```
T1 = 1
T2 = 2
T3 = T1 * T2
T4 = T1 + 3
T5 = T3 * T4
T6 = T5 / T3
OUT T5
OUT T6
```



# PROCESSOR SCHEDULING IS NP-HARD

# Processor Scheduling

- A Process Scheduling Problem can be described by
  - **m processors $P_1, P_2, \ldots, P_m$,**
  - **processor timing functions $S_1, S_2, \ldots, S_m$, each describing how the corresponding processor responds to an execution profile,**
  - **additional resources $R_1, R_2, \ldots, R_k$, e.g., memory**
  - **transmission cost matrix $C_{ij}$ ($1 \le i , j \le m$), based on proc. data sharing,**
  - **tasks to be executed $T_1, T_2, \ldots, T_n$,**
  - **task execution profiles $A_1, A_2, \ldots, A_n$,**
  - **a partial order defined on the tasks such that $T_i < T_j$ means that $T_i$ must complete before $T_j$ can start execution,**
  - **communication matrix $D_{ij}$ ($1 \le i , j \le n$); $D_{ij}$ can be non-zero only if $T_i < T_j$,**
  - **weights $W_1, W_2, \ldots, W_n$ -- cost of deferring execution of task.**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# Complexity Overview

- **The intent of a scheduling algorithm is to minimize the sum of the weighted completion times of all tasks, while obeying the constraints of the task system. Weights can be made large to impose deadlines.**
- **The general scheduling problem is quite complex, but even simpler instances, where the processors are uniform, there are no additional resources, there is no data transmission, the execution profile is just processor time and the weights are uniform, are very hard.**
- **In fact, if we just specify the time to complete each task and we have no partial ordering, then finding an optimal schedule on two processors is an NP-complete problem. It is essentially the optimization version of the Partition or equally can be viewed as a SubsetSum problem.**

# 2 Processor Scheduling

**The problem of optimally scheduling n tasks $T_1, T_2, \ldots, T_n$ onto 2 processors with an empty partial order < is the same as that of dividing a set of positive whole numbers into two subsets, such that the numbers are as close to evenly divided. So, for example, given the numbers**

**3, 2, 4, 1**

**we could try a “greedy” approach as follows:**

**put 3 in set 1**

**put 2 in set 2**

**put 4 in set 2 (total is now 6)**

**put 1 in set 1 (total is now 4)**

**This is not the best solution. A better option is to put 3 and 2 in one set and 4 and 1 in the other. Such a solution would have been attained if we did a greedy solution on a sorted version of the original numbers. In general, however, sorting doesn’t work.**

# 2 Processor Nastiness

**Try the unsorted list (result is no worse than opt * (2-1/m))**

**7, 7, 6, 6, 5, 4, 4, 5, 4**

**Greedy (Always in one that is least used)**

**7, 6, 5, 5 = 23**

**7, 6, 4, 4, 4 = 25**

**Optimal**

**7, 6, 6, 5 = 24**

**7, 4, 4, 4, 5 = 24**

**Sort it (non-increasing) (opt * (4/3-1/3m))**

**7, 7, 6, 6, 5, 5, 4, 4, 4**

**7, 6, 5, 4, 4 = 26**

**7, 6, 5, 4 = 22**

**Sort it (non-decreasing) (opt*(2-1/m))**

**4, 4, 4, 5, 5, 6, 6, 7, 7**

**4, 4, 5, 6, 7 = 26**

**4, 5, 6, 7 = 22**

**Both sorts are even worse than greedy unsorted !! (not a general result)**



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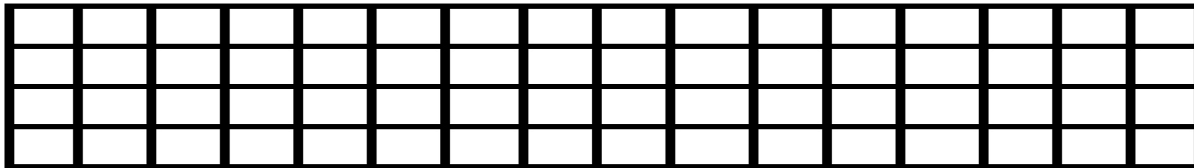
# Challenge Problem

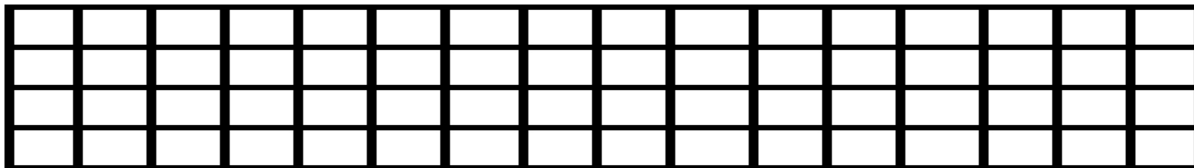
Consider the simple scheduling problem where we have a set of independent tasks running on a fixed number of processors, and we wish to minimize finishing time.

How would a list (first fit, no preemption) strategy schedule tasks with the following IDs and execution times onto four processors? Answer using Gantt chart.

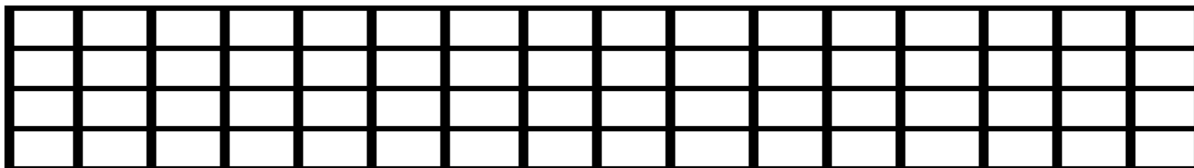
**(T1,4) (T2,1) (T3,3) (T4,6) (T5,2) (T6,1) (T7,4) (T8,5) (T9,7) (T10,3) (T11,4) (2-1/m)**



Now show what would happen if the times were sorted non-decreasing. **(2-1/m)**



Now show what would happen if the times were sorted non-increasing. **(4/3-1/3m)**

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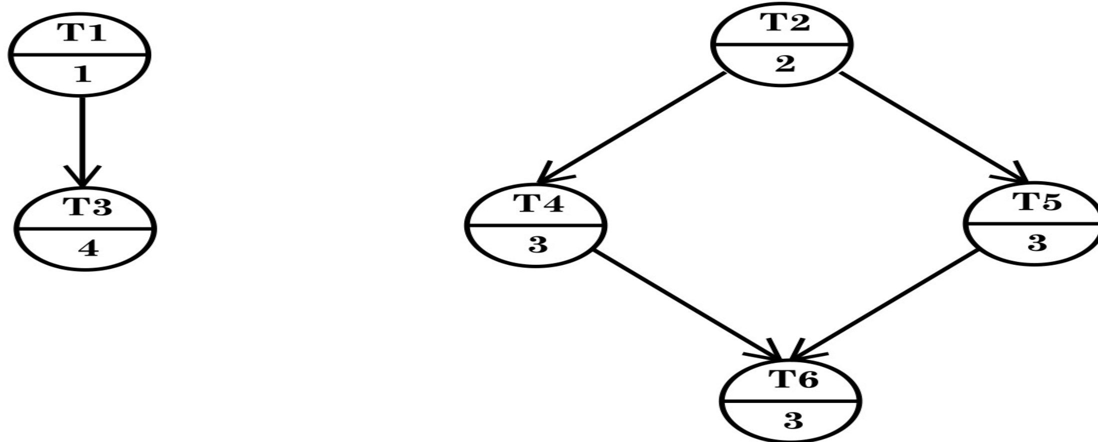
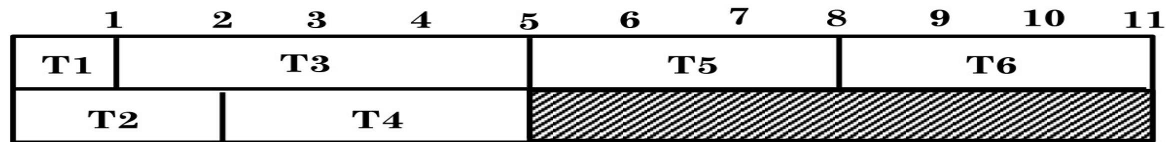
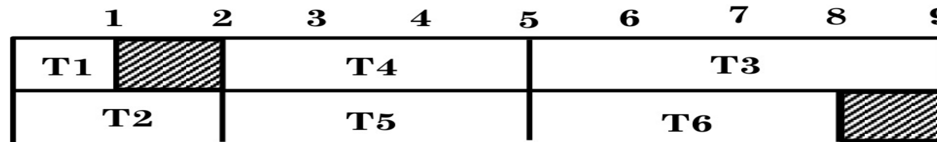
# 2 Processor with partial order

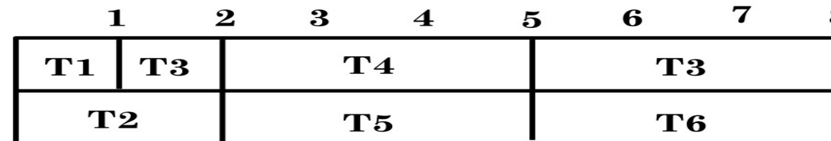



List Schedule with L = {T1,T2,T3,T4,T5,T6}




Non-Preemptive, Delays Allowed




Preemptive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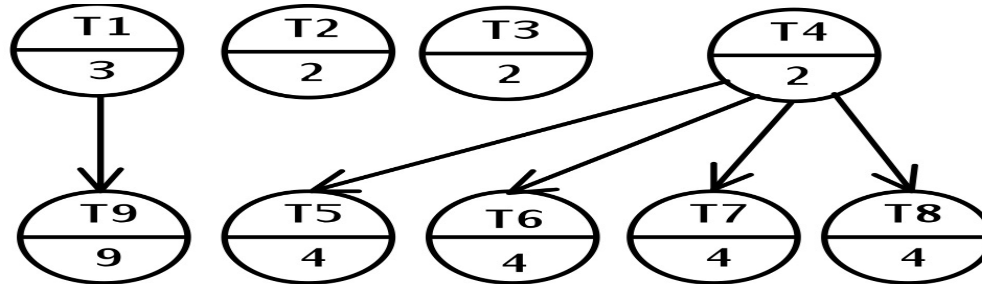
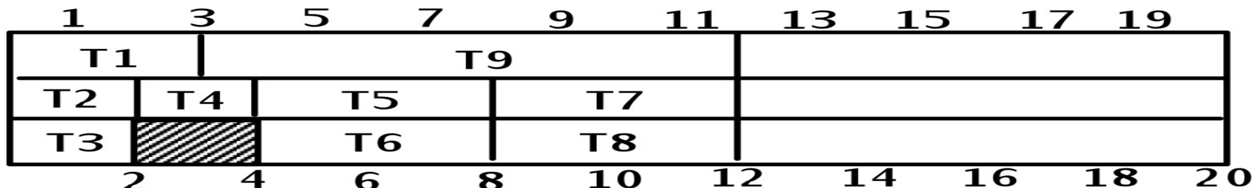
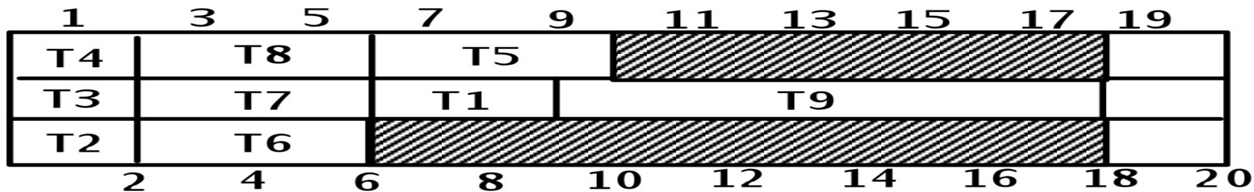
# Anomalies everywhere

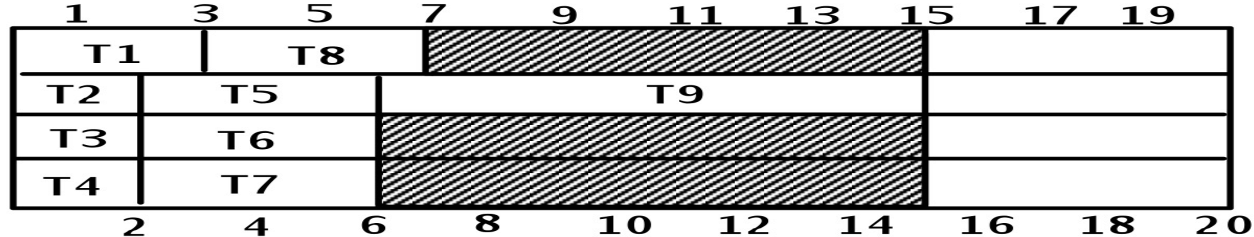



List Schedule with L = {T1,T2,T3,T4,T5,T6,T7,T8,T9




List Schedule with L = {T9,T8,T7,T6,T5,T4,T3,T2,T1




Use Original List with 4 Processors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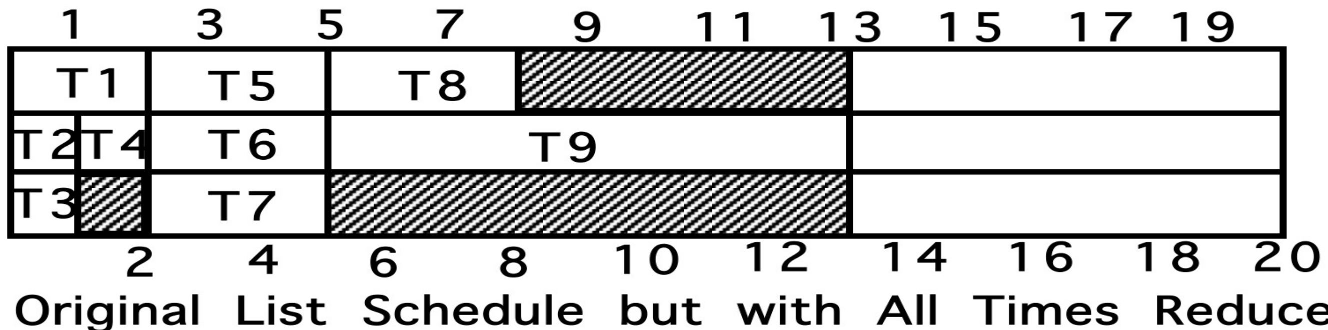
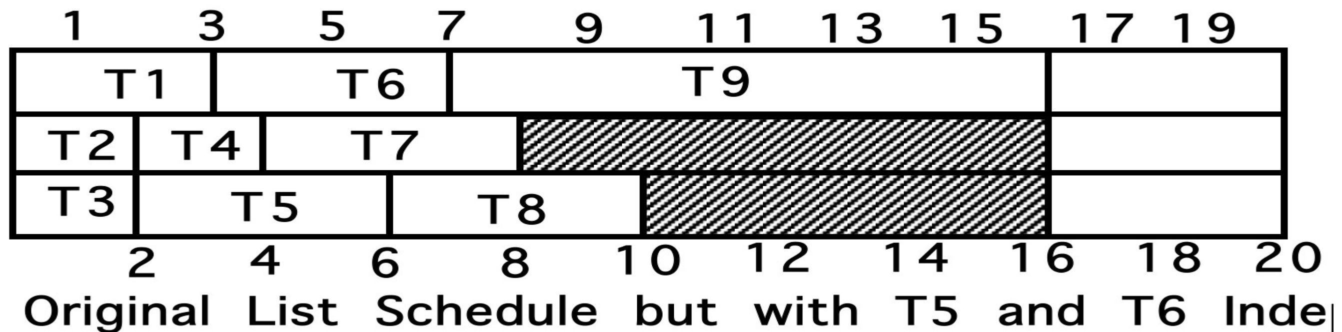
# More anomalies





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# Critical path or level strategy

A UET is a Unit Execution Tree. Our Tree is funny. It has a single leaf by standard graph definitions.

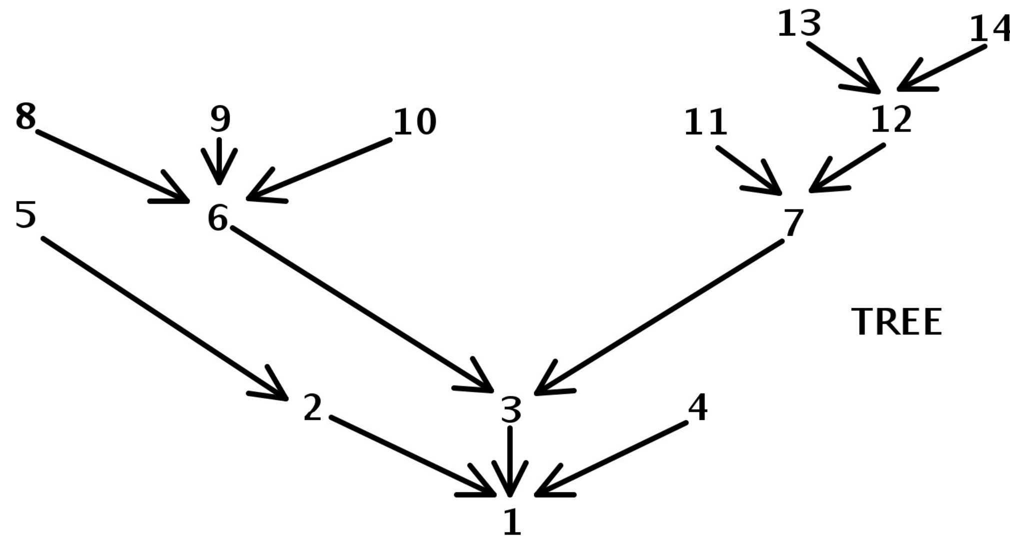
1. Assign L(T) = 1, for the leaf task T
2. Let labels 1, …, k-1 be assigned. If T is a task with lowest numbered immediate successor then define L(T) = k (non-deterministic)

   This is an order n labeling algorithm that can easily be implemented using a breadth first search.

Note: This can be used for a forest as well as a tree. Just add a new leaf. Connect all the old leafs to be immediate parents of the new one. Use the above to get priorities, starting at 0, rather than 1. Then delete the new node completely.

Note: This whole thing can also be used for anti-trees. Make a schedule, read it backwards. You cannot just reverse priorities.

# Level strategy and UET




| 14 | 12 | 8 | 6 | 3 | 1 |
|---|---|---|---|---|---|
| 13 | 10 | 7 | 4 | | |
| 11 | 9 | 5 | 2 | | |

M=3

**Theorem: Level Strategy is optimal for unit execution, m arbitrary, forest precedence**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# Level – DAG with unit time

1. Assign L(T) = 1, for an arbitrary leaf task T
2. Let labels 1, …, K-1 be assigned. For each task T such that

   { L(T') is defined for all T' in Successor(T) = S(T) }

   Let N(T) be decreasing sequence of set members in
   {S(T') | T' is in S(T)}

   Choose T* with least N(T*).
   Define L(T*) = K.

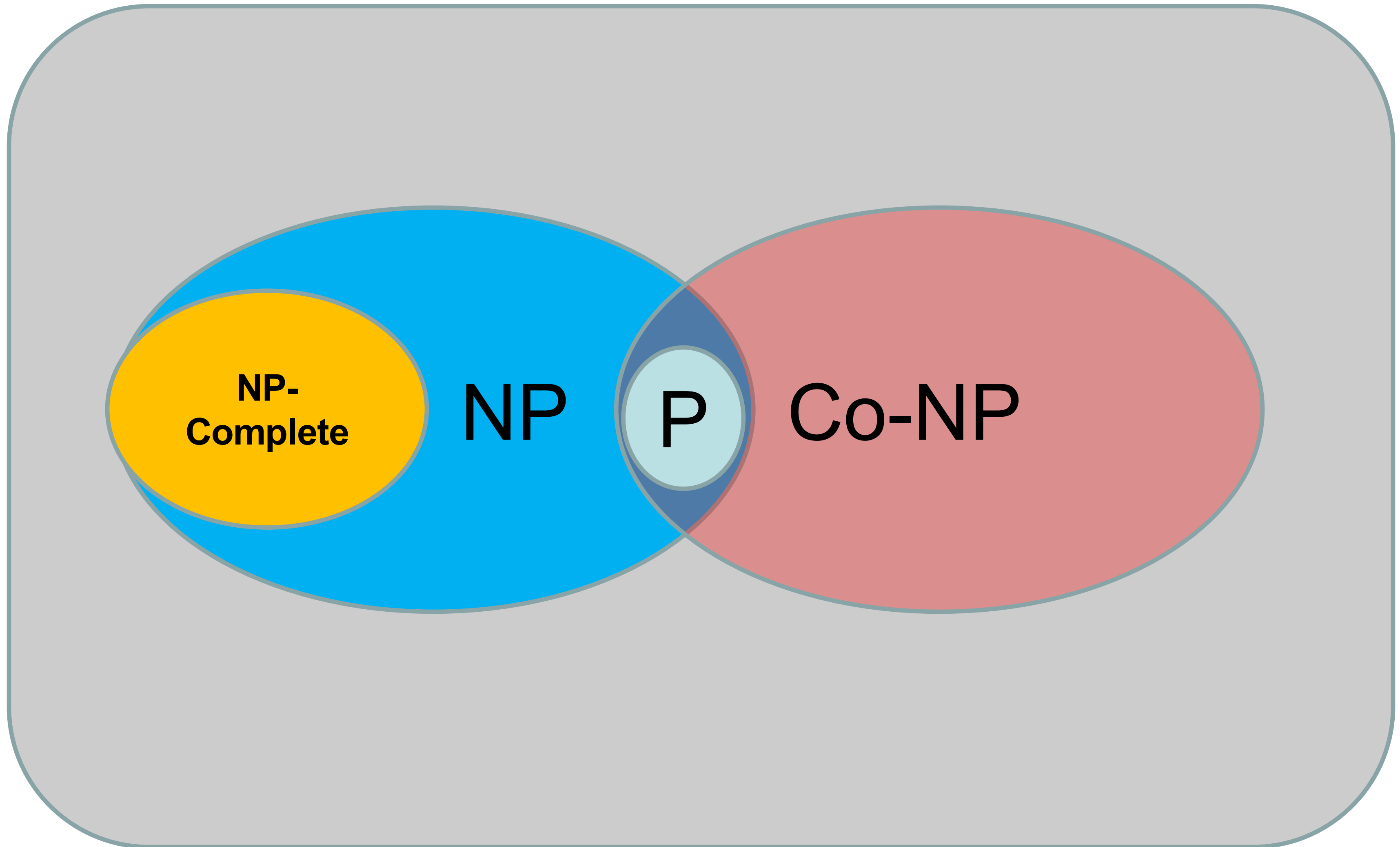
   This is an order $n^2$ labeling algorithm. Scheduling with it involves n union / find style operations. Such operations have been shown to be implementable in nearly constant time using an "amortization" algorithm.

**Theorem**: Level Strategy is optimal for unit execution, m=2, dag precedence.

# Thought Experiment

**Looking back at the UET example, consider adding two additional tasks numbered 15 and 16 that are siblings of 13 and 14. These four tasks must be completed before 12 is started.**
**a) Show the Gantt chart that reflects the new schedule associated with this enhanced tree**
**b) Show the Gantt chart that is associated with the corresponding anti-tree, in which all arcs are turned in the opposite direction. Use the technique of reversing the schedule from (a)**
**c) Show the Gantt chart associated with the anti-tree of b), where we now use the priorities obtained by treating lower numbered tasks as higher priority ones**
**d) Comment on the results seen in (b) versus (c), providing insight as to why they are different and why one is better than the other.**

# UNIVERSE OF SETS

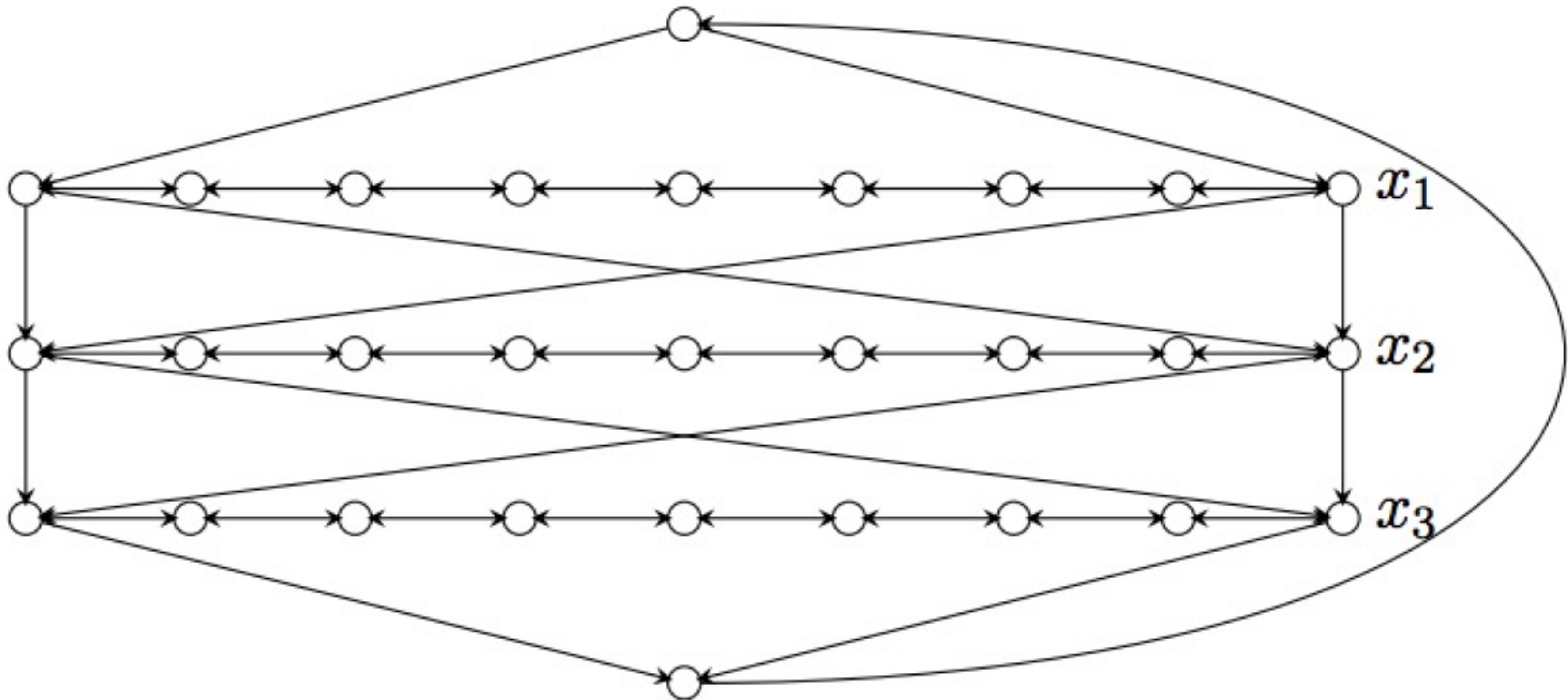


# HAMILTONIAN CIRCUIT (HC) DECISION PROBLEM IS NP-HARD

# Hamiltonian Path/Circuit

- A ***Hamiltonian Path*** is a path through a graph from one node ‘start’ to another node ‘end’ that visits every node in the graph just once.
- A ***Hamiltonian Circuit*** is a Hamiltonian Path whose end node is adjacent to its start node. It can also be viewed that the start and end nodes are the same and that the only repeated node is the start node with its only repetition being at the end of the path.

# HC Variable Gadget




This has many Hamiltonian Circuits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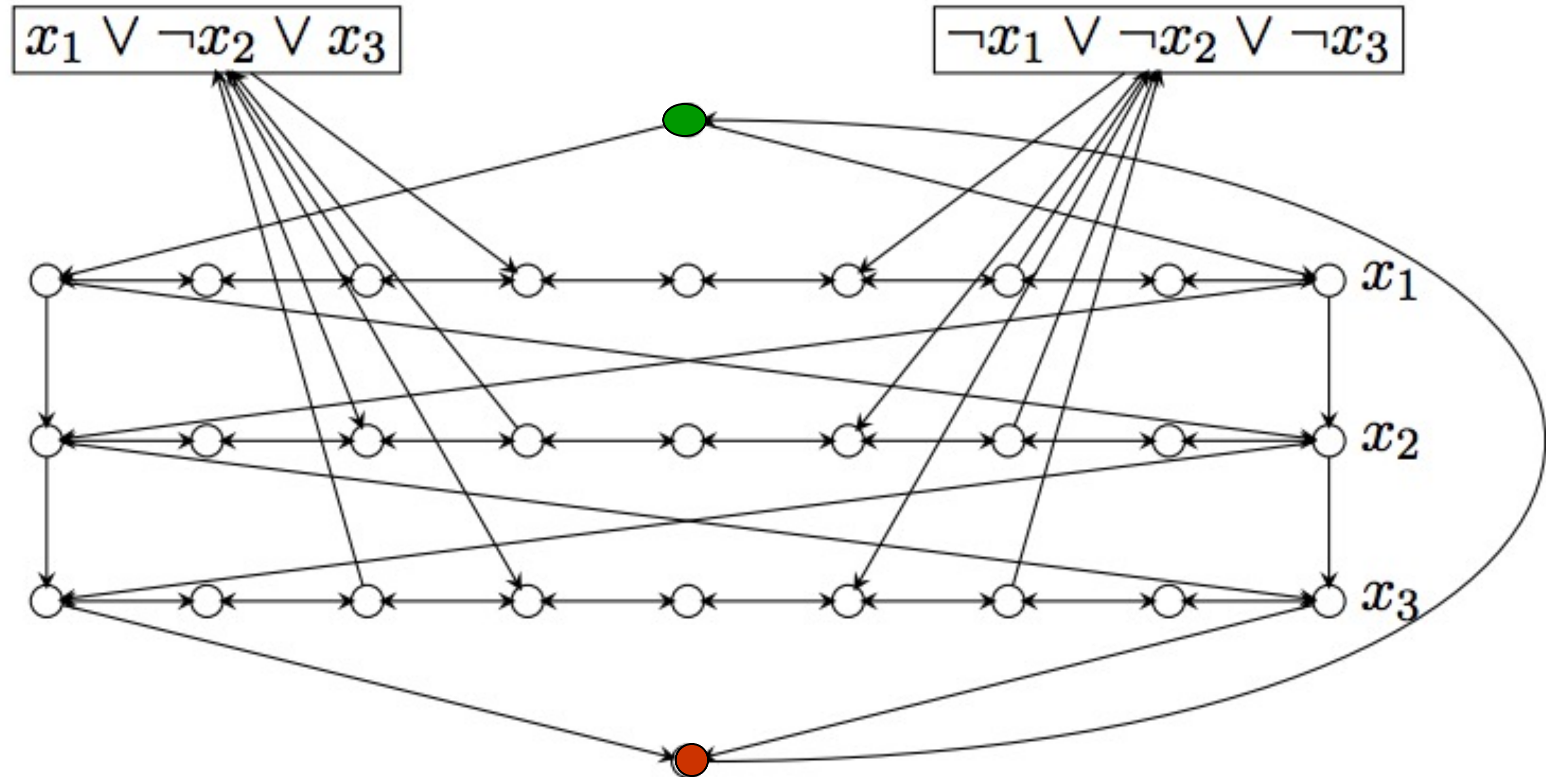
# HC Gadgets Combined

We will set convention on $x_i$ true to be left to right and $x_i$ false to be right to left (can fix for opposite)




This has a Hamiltonian Circuit iff all clauses are satisfied with consistent assignments to each variable. Note left to right assigns $X_i$ as true; right to left assigns $\neg X_i$ as true. There are filler nodes on left and right and between clauses.

# Hamiltonian Path

- Note we can split an arbitrary node, v, into two (v',v'') – one, v', has in-edges of v, other, v'', has out-edges. Path (not cycle) must start at v'' and end at v' and goal is still K (the number of vertices).

# Travelling Salesman

- ***Travelling Salesman Problem:***
  Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city and returns to the origin city?
- This is a Hamiltonian Cycle with weights on edges and we seek ***minimum*** weight for cycle.
- The decision problem version involves setting a goal weight, ***L***, and asking is we can achieve it.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# Travelling Salesman and HC

- Start with HC = (V,E), K=|V|
- Set edges from HC instance to 1
- Add edges between pairs that lack such edges and make those weights 2 (often people make these K+1); this means that the reverse of unidirectional links also get weight 2
- Goal weight is K for cycle


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# Knapsack 0-1 Problem

- The goal is to **maximize the value of a knapsack** that can hold at most W units (i.e. lbs or kg) worth of goods from a list of items $I_0, I_1, \ldots I_{n-1}$.
  - Each item has 2 attributes:
    1) Value – let this be $v_i$ for item $I_i$
    2) Weight – let this be $w_i$ for item $I_i$

Thanks to Arup Guha


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# Knapsack 0-1 Problem

- The difference between this problem and the fractional knapsack one is that you CANNOT take a fraction of an item.
  - You can either take it or leave it.
  - Hence the name Knapsack 0-1 problem.

# Knapsack Optimize vs Decide

- The optimization problem is to have the sum of the chosen values, $v_i$, to be as large as possible with the constraint that the sum of the corresponding weights, $w_i$, cannot exceed W.
- We can restate as decision problem to determine if there exists a set of items, each with equal weights and values < W, that reaches some fixed goal value, W.


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# Knapsack and SubsetSum

- Let $v_i = w_i$ for each item $I_i$.
- By doing so, the value is maximized when the Knapsack is filled as close to capacity.
- The related decision problem is to determine if we can attain capacity (W).
- Clearly then, given an instance of the SubsetSum problem, we can create an instance of the Knapsack decision problem problem, such that we reach the goal sum, G, iff we can attain a Knapsack value of G.


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# Knapsack Decision Problem

- The reduction from SubsetSum shows that the Knapsack decision problem is at least as hard as SubsetSum, so it is NP-Complete if it is in NP.
- Think about whether or not it is in NP.
- Now, think about the optimization problem.


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# Related Bin Packing

- Have a bin capacity of **B**.
- Have item set $\mathbf{S = \{s_1, s_2, \ldots, s_n\}}$
- Use all items in **S**, minimizing the number of bins, while adhering to the constraint that any such subset must sum to **B** or less.
- This is similar to the processor scheduling problem without constraints, except we optimize on number of processors, not finishing time for all tasks. It is NP-Hard (WHY?)

# Knapsack 0-1 Problem

- Brute Force
  - The naïve way to solve the 0-1 Knapsack problem is to cycle through all $2^n$ subsets of the n items and pick the subset with a legal weight that maximizes the value of the knapsack.
  - We can come up with a dynamic programming algorithm that is USUALLY faster than this brute force technique.

# Knapsack 0-1 Problem

- We are going to solve the problem in terms of sub-problems and memoization (dynamic programming).
- Our first attempt might be to characterize a sub-problem as follows:
  - Let $S_k$ be the optimal subset of elements from $\{I_0, I_1, \ldots, I_k\}$.
    - What we find is that the optimal subset from the elements $\{I_0, I_1, \ldots, I_{k+1}\}$ may not correspond to the optimal subset of elements from $\{I_0, I_1, \ldots, I_k\}$ in any regular pattern.
  - Basically, the solution to the optimization problem for $S_{k+1}$ might NOT contain the optimal solution from problem $S_k$.


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# Knapsack 0-1 Problem

- Let's illustrate that point with an example:

| Item | Weight | Value |
|---|---|---|
| $I_0$ | 3 | 10 |
| $I_1$ | 8 | 4 |
| $I_2$ | 9 | 9 |
| $I_3$ | 8 | 11 |

- **The maximum weight the knapsack can hold is 20.**

- The best set of items from $\{I_0, I_1, I_2\}$ is $\{I_0, I_1, I_2\}$
- BUT the best set of items from $\{I_0, I_1, I_2, I_3\}$ is $\{I_0, I_2, I_3\}$.
  - In this example, note that this optimal solution, $\{I_0, I_2, I_3\}$, does NOT build upon the previous optimal solution, $\{I_0, I_1, I_2\}$.
    - (Instead it builds upon the solution, $\{I_0, I_2\}$, which is really the optimal subset of $\{I_0, I_1, I_2\}$ with weight 12 or less.)

# Knapsack 0-1 problem

- So now we must re-work the way we build upon previous sub-problems…
  - Let **B[k, w]** represent the maximum total value of a subset $S_k$ with weight w.
  - Our goal is to find **B[n, W],** where n is the total number of items and W is the maximal weight the knapsack can carry.

- So our recursive formula for subproblems:

$$B[k, w] = B[k-1, w], \text{ if } w_k > w$$
$$= \max \{ B[k-1, w], B[k-1, w-w_k] + v_k \}, \text{ otherwise}$$

- In English, this means that the best subset of $S_k$ that has total weight w is:
  1) The best subset of $S_{k-1}$ that has total weight w, or
  2) The best subset of $S_{k-1}$ that has total weight $w-w_k$ plus the item k

# Knapsack 0-1 Problem – Recursive Formula

$$B[k, w] = \begin{cases} B[k-1, w], & \text{if } w_k > w \\ \max\{ B[k-1, w],\ B[k-1, w-w_k] + v_k \}, & \text{otherwise} \end{cases}$$

- The best subset of $S_k$ that has the total weight w, either contains item k or not.

- **First case:** $w_k > w$
  - Item *k* can't be part of the solution! If it was the total weight would be > w, which is unacceptable.

- **Second case:** $w_k \leq w$
  - Then the item *k* can be in the solution, and we choose the case with greater value.

# Knapsack 0-1 Algorithm

```
for w = 0 to W          // Initialize 1st row to 0's
   B[0,w] = 0
for i = 1 to n          // Initialize 1st column to 0's
   B[i,0] = 0
for i = 1 to n
   for w = 1 to W
       if wi <= w      //item i can be in the solution
             if vi + B[i-1,w-wi] > B[i-1,w]
                    B[i,w] = vi + B[i-1,w- wi]
             else
                    B[i,w] = B[i-1,w]
       else B[i,w] = B[i-1,w] // wi > w
}
```



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# Knapsack 0-1 Problem

- Let's run our algorithm on the following data:
  - n = 4 (# of elements)
  - W = 5 (max weight)
  - Elements (weight, value):
    (2,3), (3,4), (4,5), (5,6)


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# Knapsack 0-1 Example

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | | | | | |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |

```
// Initialize the base cases
for w = 0 to W
        B[0,w] = 0

for i = 1 to n
        B[i,0] = 0
```

# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | | | | |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |

$i = 1$
$v_i = 3$
$w_i = 2$
$w = 1$
$w\text{-}w_i = -1$

if $w_i <= w$ //item i can be in the solution

if $v_i + B[i-1,w-w_i] > B[i-1,w]$

$B[i,w] = v_i + B[i-1,w- w_i]$

else

$B[i,w] = B[i-1,w]$

else **B[i,w] = B[i-1,w]** // $w_i > w$

# Knapsack 0-1 Example

Items:

1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | | | |
| **2** | 0 | | | | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 1$
$v_i = 3$
$w_i = 2$
$\mathbf{w = 2}$
$w\text{-}w_i = 0$

if $w_i <= w$ //item i can be in the solution

  if $v_i + B[i-1,w-w_i] > B[i-1,w]$

    $B[i,w] = v_i + B[i-1,w- w_i]$

  else

    $B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$

# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | | |
| **2** | 0 | | | | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 1$
$v_i = 3$
$w_i = 2$
$\mathbf{w = 3}$
$w - w_i = 1$

if $w_i <= w$ //item i can be in the solution
  if $v_i + B[i-1,w-w_i] > B[i-1,w]$
    **$B[i,w] = v_i + B[i-1,w- w_i]$**
  else
    $B[i,w] = B[i-1,w]$
else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | |
| **2** | 0 | | | | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 1$
$v_i = 3$
$w_i = 2$
$\mathbf{w = 4}$
$w - w_i = 2$

if $w_i$ <= w //item i can be in the solution

if $v_i + B[i-1, w-w_i] > B[i-1, w]$

**$B[i,w] = v_i + B[i-1, w-w_i]$**

else

$B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | | | | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 1$
$v_i = 3$
$w_i = 2$
$\mathbf{w = 5}$
$w\text{-}w_i = 3$

if $w_i$ <= w //item i can be in the solution

if $v_i + B[i-1,w-w_i] > B[i-1,w]$

**$B[i,w] = v_i + B[i-1,w- w_i]$**

else

$B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$

# Knapsack 0-1 Example

Items:

1: (2,3)

2: (3,4)

3: (4,5)

4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | | | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 2$

$v_i = 4$

$w_i = 3$

$\mathbf{w = 1}$

$w\text{-}w_i = -2$

if $w_i <= w$ //item i can be in the solution

    if $v_i + B[i-1,w-w_i] > B[i-1,w]$

        $B[i,w] = v_i + B[i-1,w- w_i]$

    else

        $B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 2$
$v_i = 4$
$w_i = 3$
$\mathbf{w = 2}$
$w\text{-}w_i = -1$

if $w_i <= w$ //item i can be in the solution
  if $v_i + B[i-1,w-w_i] > B[i-1,w]$
    $B[i,w] = v_i + B[i-1,w- w_i]$
  else
    $B[i,w] = B[i-1,w]$
else **B[i,w] = B[i-1,w]** // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 2$
$v_i = 4$
$w_i = 3$
$\mathbf{w = 3}$
$w\text{-}w_i = 0$

if $w_i$ <= w //item i can be in the solution

if $v_i + B[i-1,w-w_i] > B[i-1,w]$

**$B[i,w] = v_i + B[i-1,w- w_i]$**

else

$B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | 4 | |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 2$
$v_i = 4$
$w_i = 3$
$\mathbf{w = 4}$
$w\text{-}w_i = 1$

if $w_i <= w$ //item i can be in the solution

if $v_i + B[i-1,w-w_i] > B[i-1,w]$

**$B[i,w] = v_i + B[i-1,w- w_i]$**

else

$B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| **i / w** | **0** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | 4 | 7 |
| **3** | 0 | | | | | |
| **4** | 0 | | | | | |

$i = 2$
$v_i = 4$
$w_i = 3$
$\mathbf{w = 5}$
$w\text{-}w_i = 2$

if $w_i <= w$ //item i can be in the solution

if $v_i + B[i-1,w-w_i] > B[i-1,w]$

**$B[i,w] = v_i + B[i-1,w- w_i]$**

else

$B[i,w] = B[i-1,w]$

else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | 4 | 7 |
| **3** | 0 | 0 | 3 | 4 | | |
| **4** | 0 | | | | | |

$i = 3$
$v_i = 5$
$w_i = 4$
**$w = 1..3$**
$w\text{-}w_i = -3..-1$

if $w_i <= w$ //item i can be in the solution
    if $v_i + B[i-1,w-w_i] > B[i-1,w]$
        $B[i,w] = v_i + B[i-1,w- w_i]$
    else
        $B[i,w] = B[i-1,w]$
else **$B[i,w] = B[i-1,w]$** // $w_i > w$

# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | 4 | 7 |
| **3** | 0 | 0 | 3 | 4 | 5 | |
| **4** | 0 | | | | | |

$i = 3$
$v_i = 5$
$w_i = 4$
$\mathbf{w = 4}$
$w - w_i = 0$

if $w_i <= w$ //item i can be in the solution
 if $v_i + B[i-1,w-w_i] > B[i-1,w]$
  **$B[i,w] = v_i + B[i-1,w- w_i]$**
 else
  $B[i,w] = B[i-1,w]$
else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | 4 | 7 |
| **3** | 0 | 0 | 3 | 4 | 5 | 7 |
| **4** | 0 | | | | | |

$i = 3$
$v_i = 5$
$w_i = 4$
$\mathbf{w = 5}$
$w - w_i = 1$

if $w_i \le w$ //item i can be in the solution

  if $v_i + B[i-1,w-w_i] > B[i-1,w]$

    $B[i,w] = v_i + B[i-1,w- w_i]$

  else

    **B[i,w] = B[i-1,w]**

else $B[i,w] = B[i-1,w]$ // $w_i > w$

# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 3 | 3 | 3 | 3 |
| 2 | 0 | 0 | 3 | 4 | 4 | 7 |
| 3 | 0 | 0 | 3 | 4 | 5 | 7 |
| 4 | 0 | 0 | 3 | 4 | 5 | |

$i = 4$
$v_i = 6$
$w_i = 5$
**$w = 1..4$**
$w - w_i = -4..-1$

if $w_i <= w$ //item i can be in the solution

if $v_i + B[i-1,w-w_i] > B[i-1,w]$

$B[i,w] = v_i + B[i-1,w- w_i]$

else

$B[i,w] = B[i-1,w]$

else **$B[i,w] = B[i-1,w]$** // $w_i > w$

# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 3 | 3 | 3 | 3 |
| 2 | 0 | 0 | 3 | 4 | 4 | 7 |
| 3 | 0 | 0 | 3 | 4 | 5 | 7 |
| 4 | 0 | 0 | 3 | 4 | 5 | 7 |

$i = 4$
$v_i = 6$
$w_i = 5$
$\mathbf{w = 5}$
$w-w_i = 0$

if $w_i <= w$ //item i can be in the solution

  if $v_i + B[i-1,w-w_i] > B[i-1,w]$

    $B[i,w] = v_i + B[i-1,w- w_i]$

  else

    **$B[i,w] = B[i-1,w]$**

else $B[i,w] = B[i-1,w]$ // $w_i > w$


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# Knapsack 0-1 Example

Items:
1: (2,3)
2: (3,4)
3: (4,5)
4: (5,6)

| i / w | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 0 | 3 | 3 | 3 | 3 |
| **2** | 0 | 0 | 3 | 4 | 4 | 7 |
| **3** | 0 | 0 | 3 | 4 | 5 | 7 |
| **4** | 0 | 0 | 3 | 4 | 5 | 7 |

We're DONE!!

The max possible value that can be carried in this knapsack is ***$7***


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# Knapsack 0-1 Problem – Run Time

```
for w = 0 to W
    B[0,w] = 0
```

**O(*W*)**

```
for i = 1 to n
    B[i,0] = 0
```

**O(*n*)**

```
for i = 1 to n
    for w = 0 to W
        < the rest of the code >
```

**Repeat *n* times**

**O(*W*)**

What is the running time of this algorithm?

**O(*n*W*) *– of course, W can be mighty big***

***What is an analogy in world of sorting?***

Remember that the brute-force algorithm takes: **O(2$^n$)**


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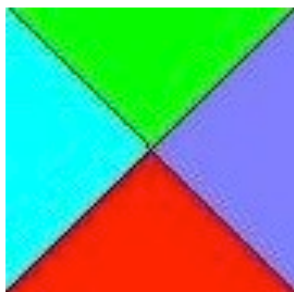
# Tiling

**Undecidable, NP-Complete, and Easy Variants**

# Basic Idea of Tiling



A single tile has colors on all four sides.
Tiles are often called dominoes as
assembling them follows the rules of
placing dominoes. That is, the color
(or number) of a side must match that
of its adjacent tile, e.g., tile, t2, to right
of a tile, t1, must have same color on
Its left as is on the right side of t1.
This constraint applies to top and bottom as
well as sides. Boundary tiles do not necessarily
have constraints on their sides that touch
the boundaries, but these can be forced.

I chose to have each tile have a mirror tile
in the vertical and horizontal directions.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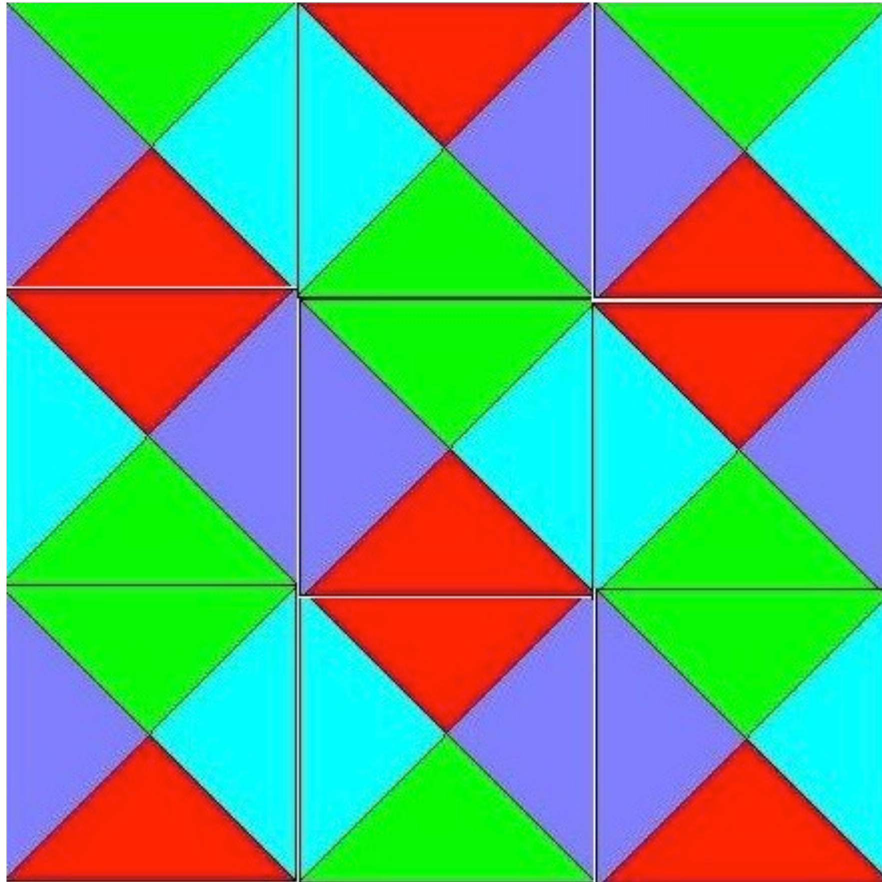
# Instance of Tiling Problem

- A finite set of tile types (a type is determined by the colors of its edges)
- Some 2d area (finite or infinite) on which the tiles are to be laid out
- An optional starting set of tiles in fixed positions
- The goal is to tile the plane following the adjacency constraints and whatever constraints are indicated by the starting configuration.

# A Valid 3 by 3 Tiling of Tile Types from a Previous Slide

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# Some Variations

- Infinite 2d plane (impossible, co-re-non-rec) in general
  - Our four tile types can easily tile the 2d plane
- Finite 2d plane (hard in general)
  - Our four tile types can easily tile any finite 2d plane
  - This is called the **Bounded Tiling Problem**
- One-dimensional space
  - This is related to cycles in a directed graph
    Each tile type **A** is a vertex
    if tile **A** has right color **c** and tile **B** has left color **c** then draw a directed edge form vertex **A** to vertex **B**
    There's a cycle iff we can infinitely tile along x-axis

# Tiling the Plane

- We will start with a Post Machine, $M = (Q, \Sigma, \delta, q_0)$, with tape alphabet $\Sigma = \{B,1\}$ where B is blank and $\delta$ maps pairs from $Q \times \Sigma$ to $Q \times (\Sigma \cup \{R,L\})$. M starts in state $q_0$
  - (Turing Machine with each action being L, R or Print)
- We will consider the case of M starting with a blank tape
- We will constrain our machine to never go to the left of its starting position (semi unbounded tape)
- We will mimic the computation steps of M
- Termination occurs if in state q reading b and $\delta(q,b)$ is not defined
- We will use the fact that halting when starting at the left end of a semi unbounded tape in its initial state with a blank tape is undecidable; we will actually look at complement of this

# The Tiling Decision Problem

- Given a finite set of tile types and a starting tile in lower left corner of 2d plane, can we tile all places in the plane?
- A place is defined by its coordinates (x,y), $x \geq 0$, $y \geq 0$
- The fixed starting tile is at (0,0)


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# Colors

- Given M, define our tile colors as
- $\{X, Y, *, B, 1, YB, Y1\} \cup Q \times \{B,1\} \cup Q \times \{YB,Y1\} \cup Q \times \{R,L\}$
- X appears only on bottom of any and all tiles that are resting on the X-axis
- Y appears only on left of any and all tiles that are adjacent to the Y-axis
- Y is part of the label on top of any tile with its left side adjacent to the Y-axis


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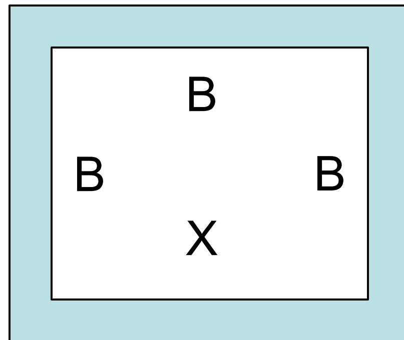
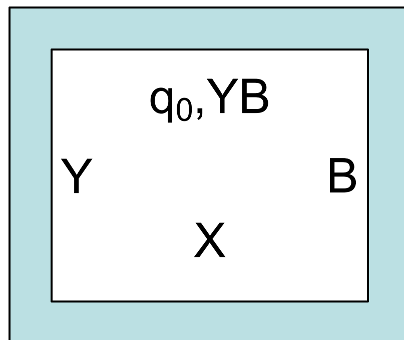
# Simple Tiles

- Simplest tile (represents Blank on X axis)




Note that these can lead to an unbounded linear replication of blanks

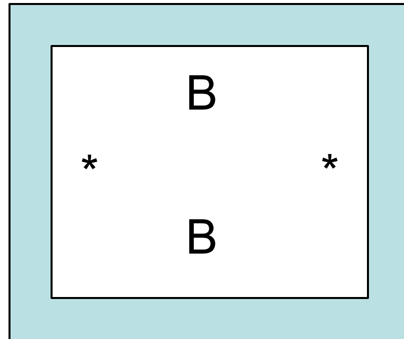
- Start tile (state q0; scanned symbol blank)

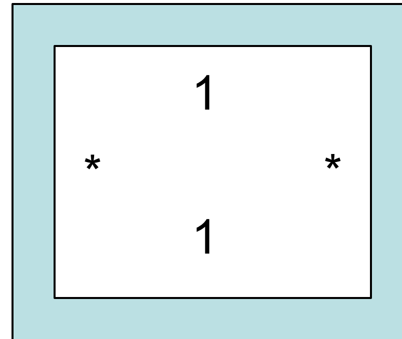



Note that the only tile with B on the left is the above one, leading to all blanks along X axis

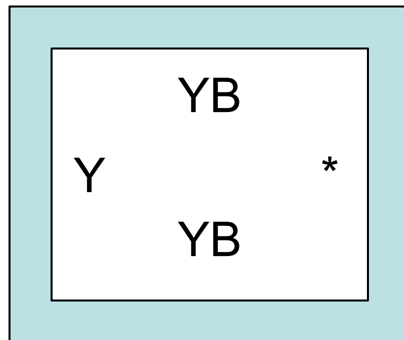
Note that a single tile is used for state and scanned square

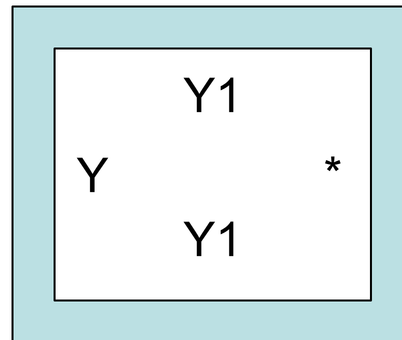
# Tiles for Copying Tape Cell




Copy cells not on left boundary except the scanned square




Copy cells on left boundary except the scanned square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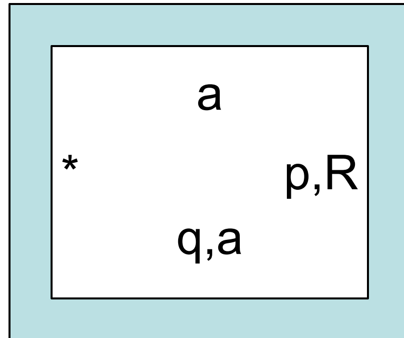
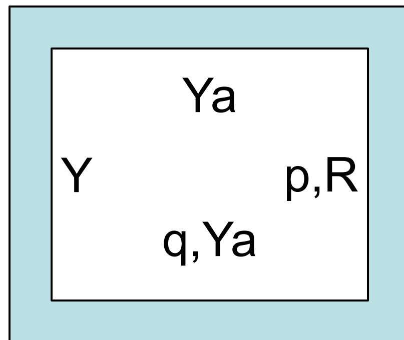
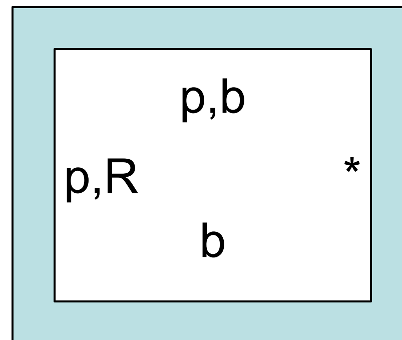
# Right Move δ(q,a) = (p,R)

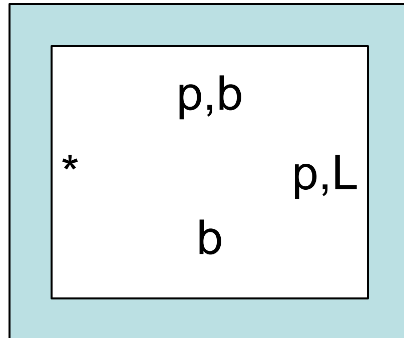


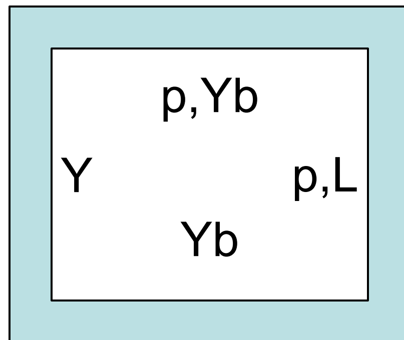



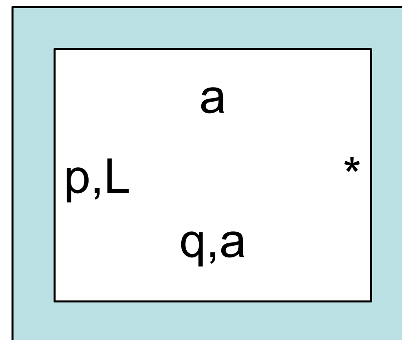




where $b \in \Sigma = \{B,1\}$

# Left Move δ(q,a) = (p,L)




where $b \in \Sigma=\{B,1\}$

No possibility of moving left if at the left end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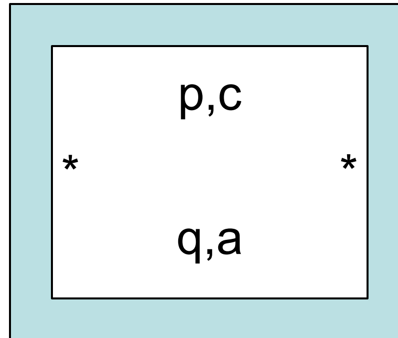
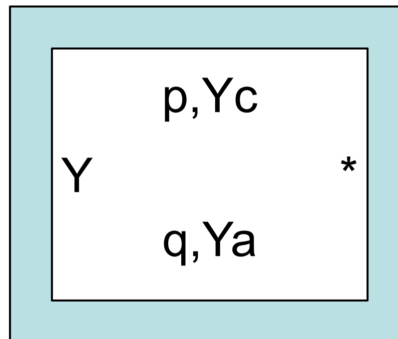
# Print $\delta(q,a) = (p,c)$





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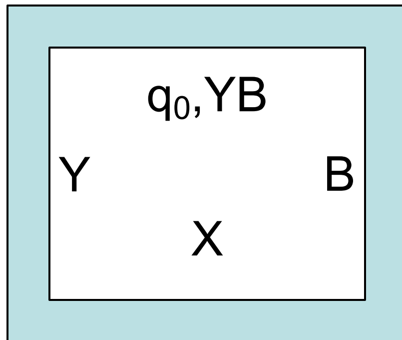
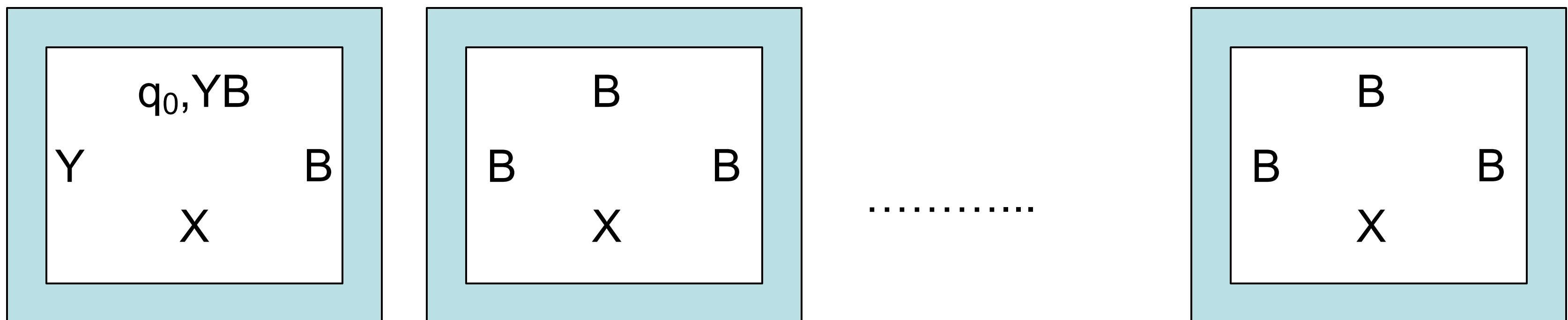
# Corner Tile and Bottom Row

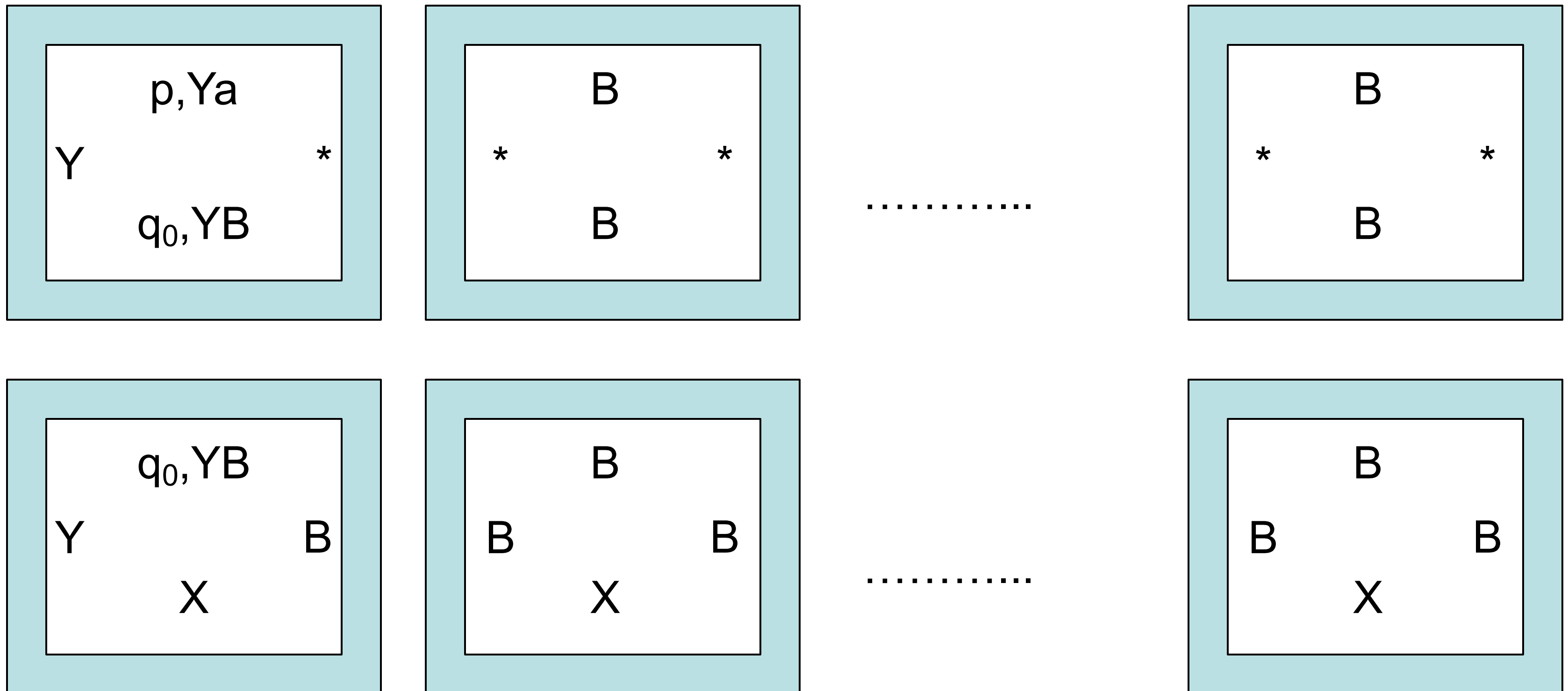



Zero-ed Row is forced to be



# First Action Print

As we cannot move left of leftmost character first action is either right or print.
Assume for now that $\delta(q_0,B) = (p,a)$





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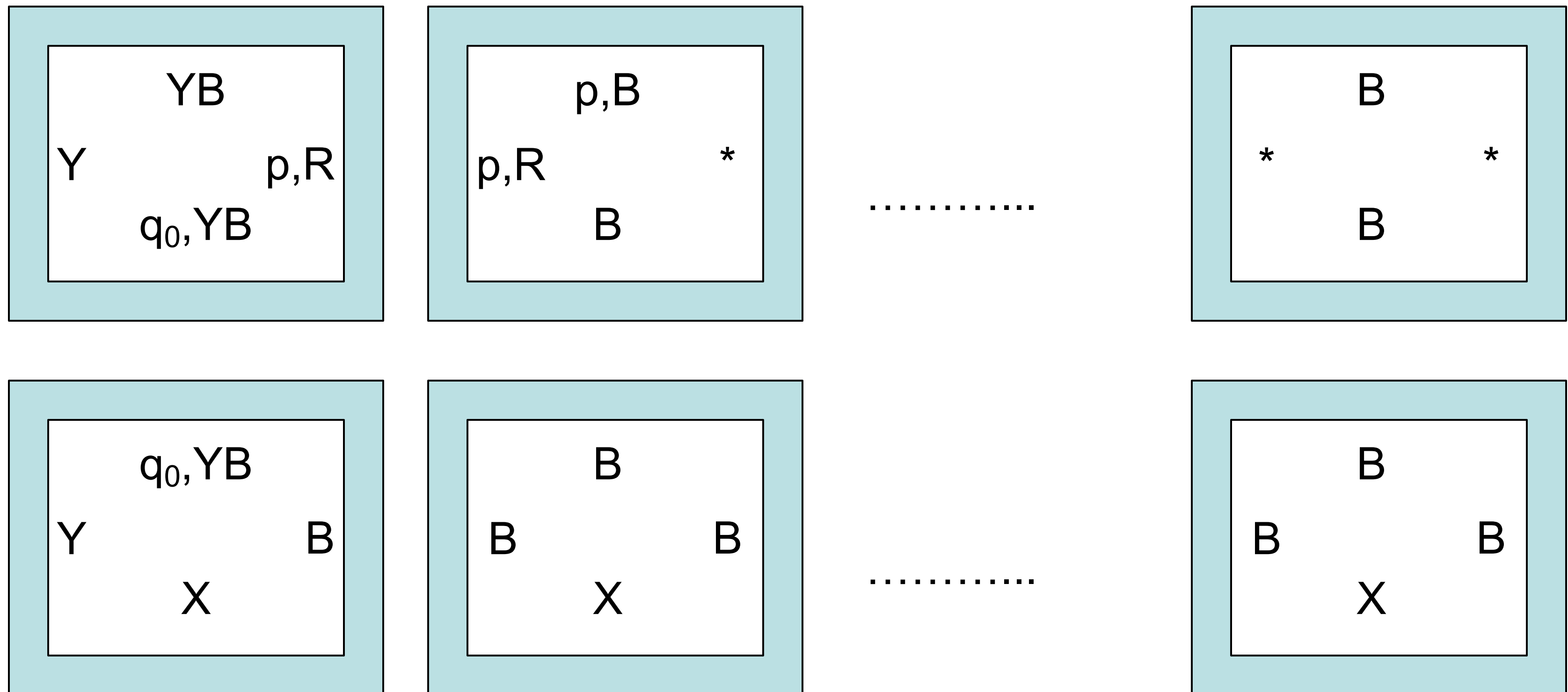
# First Action Right Move

As we cannot move left of leftmost character first action is either right or print.
Assume for now that $\delta(q_0,B) = (p,R)$



# The Rest of the Story Part 1

- Inductively we can show that, if the i-th row represents an infinite transcription of the Turing configuration after step i then the (i+1)-st represents such a transcription after step i+1. Since we have shown the base case, we have a successful simulation.

# The Rest of the Story Part 2

- Consider the case where M eventually halts when started on a blank tape in state $q_0$. In this case we will reach a point where no actions fill the slots above the one representing the current state. That means that we cannot tile the plane.
- If M never halts, then we can tile the plane (in the limit).

# The Rest of the Story Part 3

- The consequences of Parts 1 and 2 are that Tiling the plane is as hard as the complement of the Halting problem ($\forall$t [~STP(M, 0, t)]) //0 (tape is blank) which is co-RE Complete.
- This is not surprising as this problem involve a universal quantification over all coordinates (x,y) in the plane.

# Constraints on M

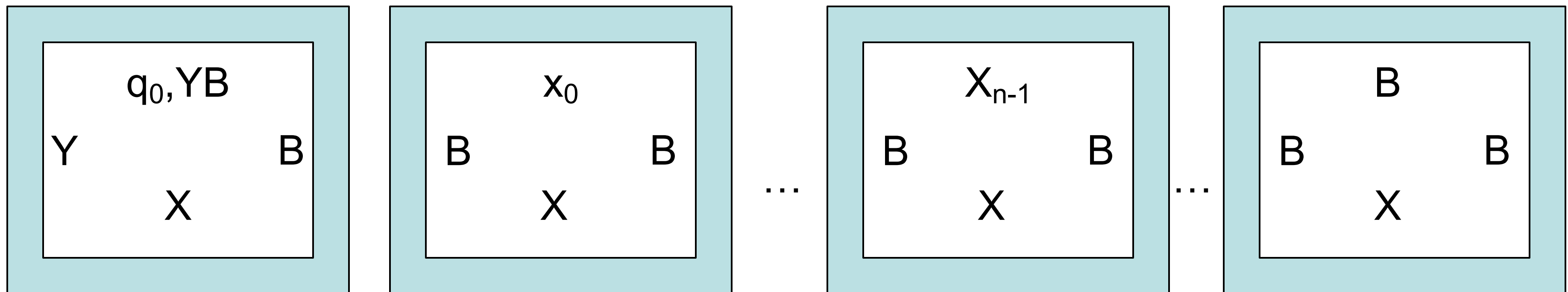
- The starting blank tape is not a real constraint as we can create M so its first actions are to write arguments on its tape.
- The semi unbounded tape is not new. If you look back at Standard Turing Computing (STC), we assumed there that we never moved left of the blank preceding our first argument.
- If you prefer to consider all computation based on the STC model, then we can add to M the simple prologue $(R1)^{x1}R(R1)^{x2}R\ldots(R1)^{xk}R$ so the actual computation starts with a vector of x1 … xk on the tape and with the scanned square as the blank to the right of this vector. The rest of the tape is blank.
- Think about how, in the preceding pages, you could start the tiling in this configuration.

# Bounded Tiling Problem #1

- Consider a slight change to our machine M. First, it is non-deterministic, so our transition function maps to sets.
- Second, we add two auxiliary states $\{q_a, q_r\}$, where $q_a$ is our only accept state and $q_r$ is our only reject state.
- We make it so the reject state has no successor states, but the accept state always transitions back to itself rewriting the scanned square unchanged.
- We also assume our machine accepts or rejects in at most $n^k$ steps, where n is the length of its starting input which is written immediately to the right of the initial scanned square.

# Bounded Tiling Problem #2

- We limit our rows and column to be of size $n^k+1$. We change our initial condition of the tape to start with the input to M. Thus, it looks like




- Note that there are $n^k – n$ of these blank representations at the end.

# Bounded Tiling Problem #3

- The finitely bounded Tiling Problem we just described mimics the operation of any given polynomially-bound non-deterministic Turing machine (this could have been our starting point, rather than SAT).
- This machine can tile the finite plane of size $(n^k+1) * (n^k+1)$ just in case the initial string is accepted in $n^k$ or fewer steps on some path (really a trace of at most $n^k$).
- If the string is not accepted, then we will hit a reject state on all paths and never complete tiling.(assume reject occurs in $< n^k$ time)
- This shows that the bounded tiling problem is NP-Hard
- Is it in NP? Yes. How? Well, we can be shown a tiling (posed solution takes space polynomial in n) and check it for completeness and consistency (this takes linear time in terms of proposed solution). Thus, we can verify the solution in time polynomial in n.

# A Final Comment on Tiling

- If you look back at the unbounded version, you can see that we could have simulated a non-deterministic Turing machine there, but it would have had the problem that the plane would be tiled if any of the non-deterministic choices diverged and that is not what we desired.
- However, we need to use a non-deterministic machine for the finite case as we made this so it tiled iff some path led to acceptance. If all lead to rejection, we get stalled out on all paths as the reject state can go nowhere.

# Tiling Example

- Turing Machine Recognizes strings of at least two 1's in succession.
- q0 0 0 q2
- q0 1 R q1
- q1 0 L q2
- q1 1 1 q3
- q2 0 0 q2
- q2 1 1 q2
- No q3 rules so entering here stops tiling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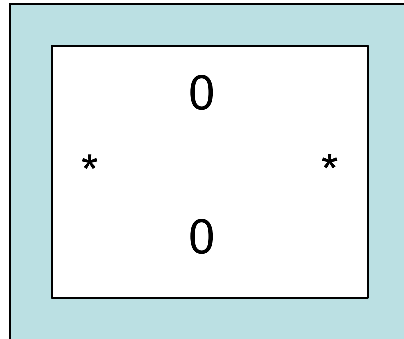
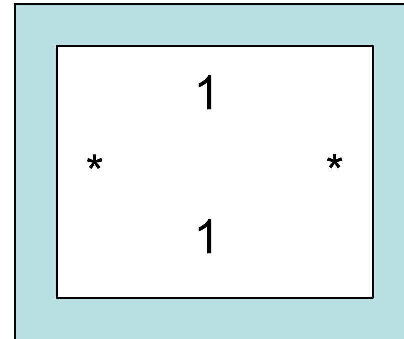
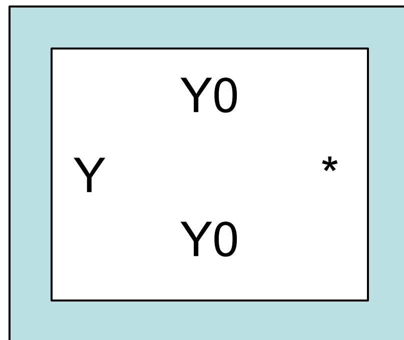
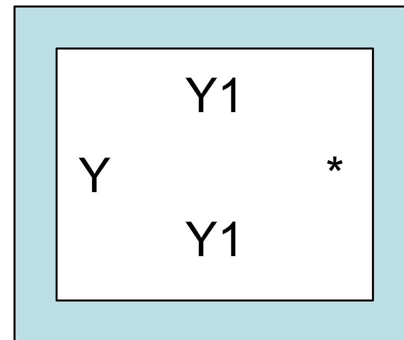
# Tile Replication





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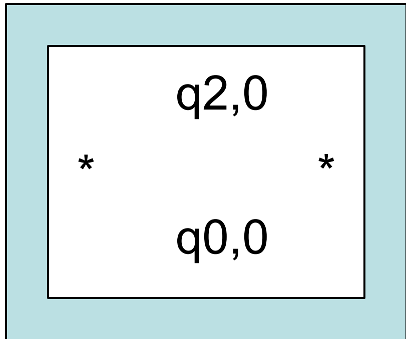
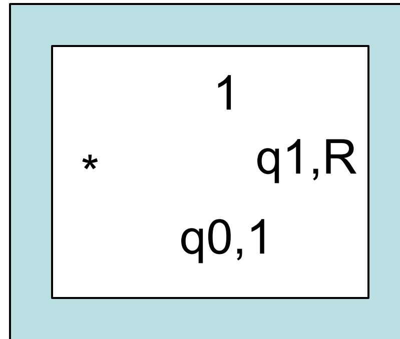
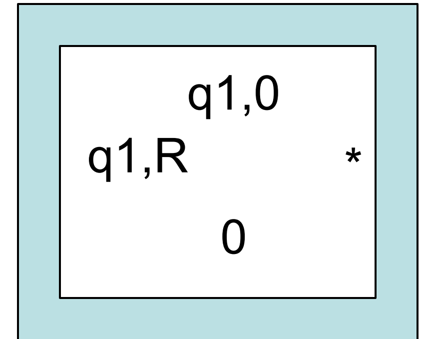
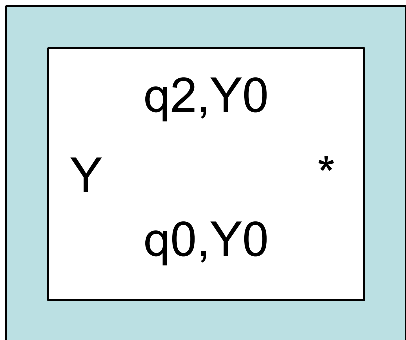
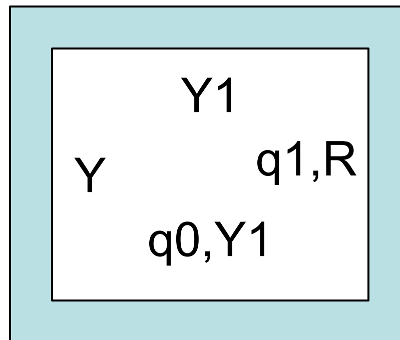
# q0 0 0 q2 q0 1 R q1

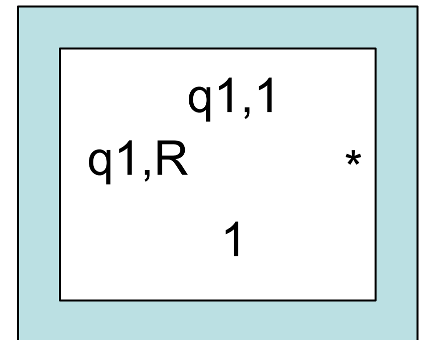




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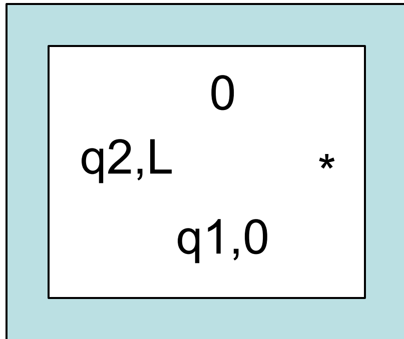
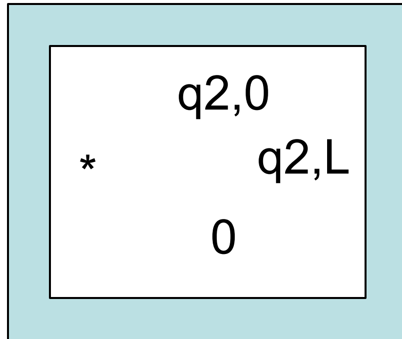
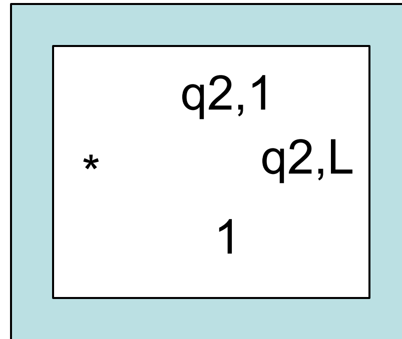
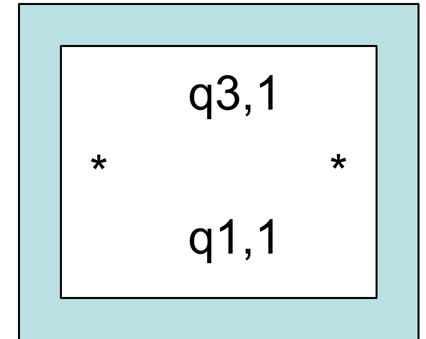
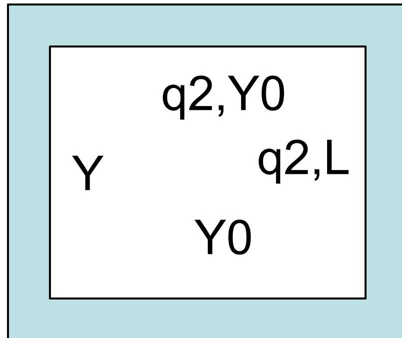
# q1 0 L q2 q1 1 1 q3

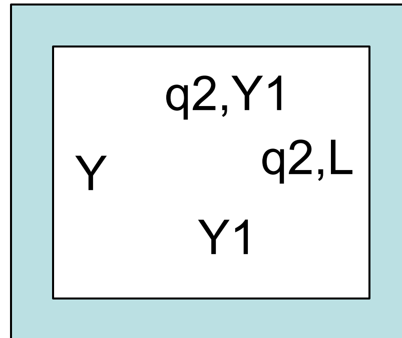


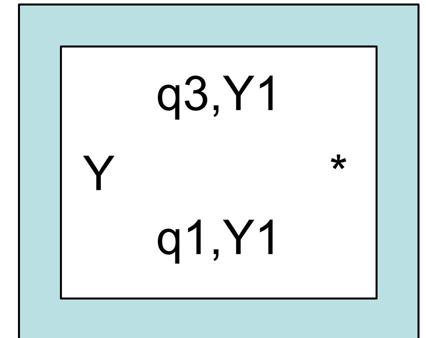



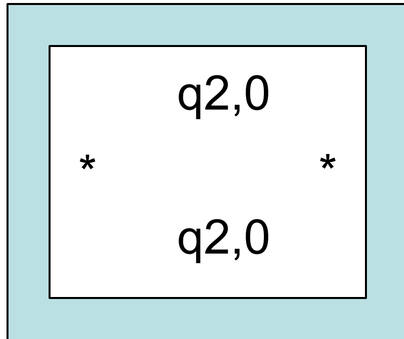



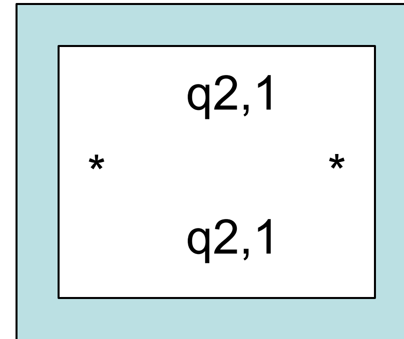



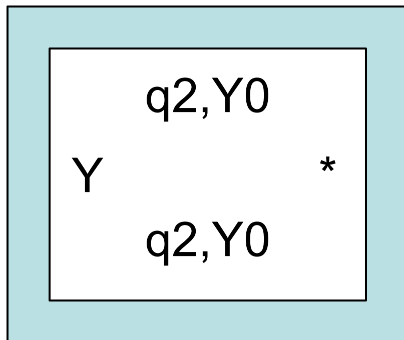



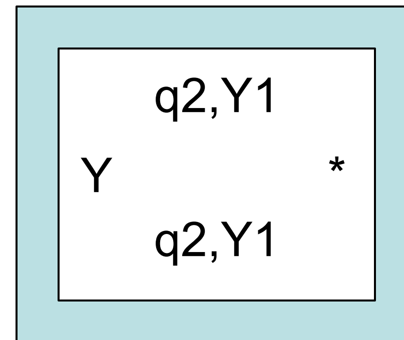



# q2 0 0 q2 q2 1 1 q2





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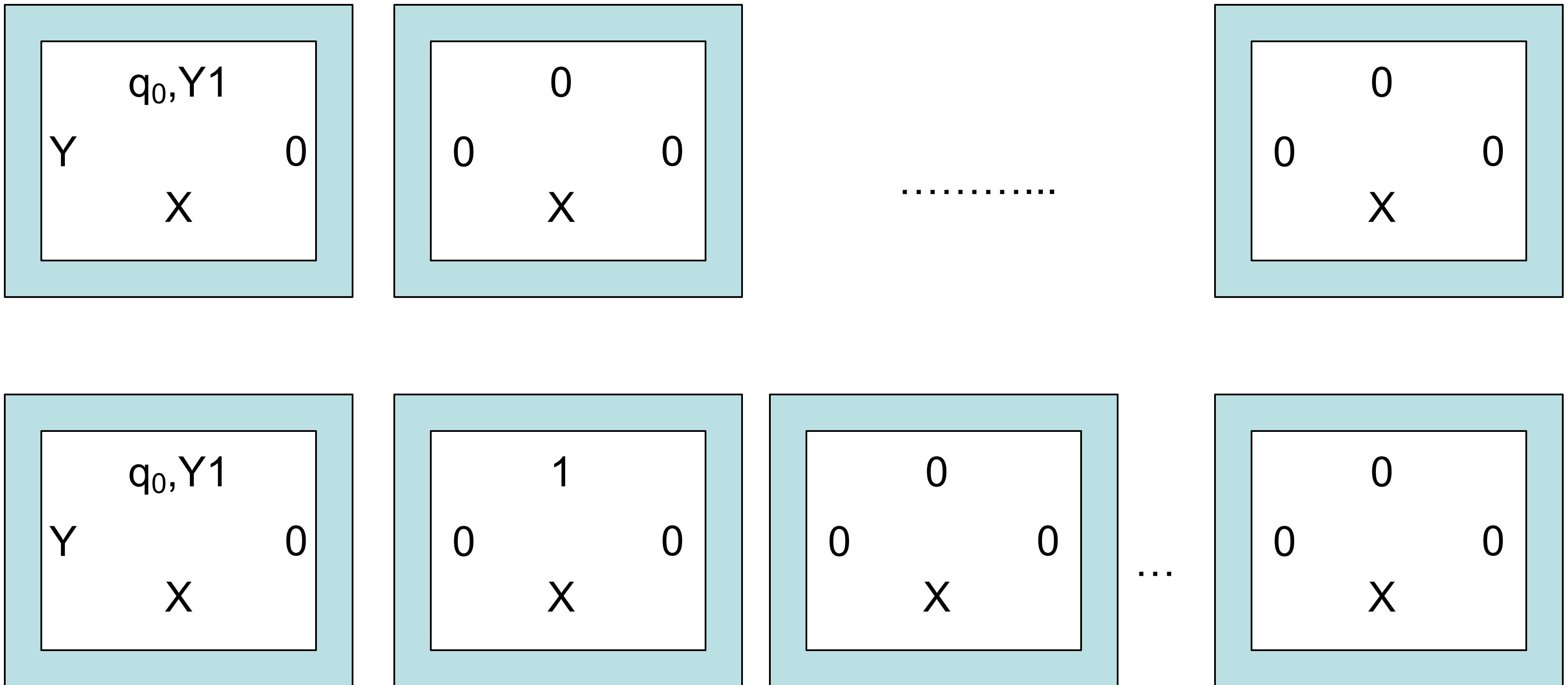
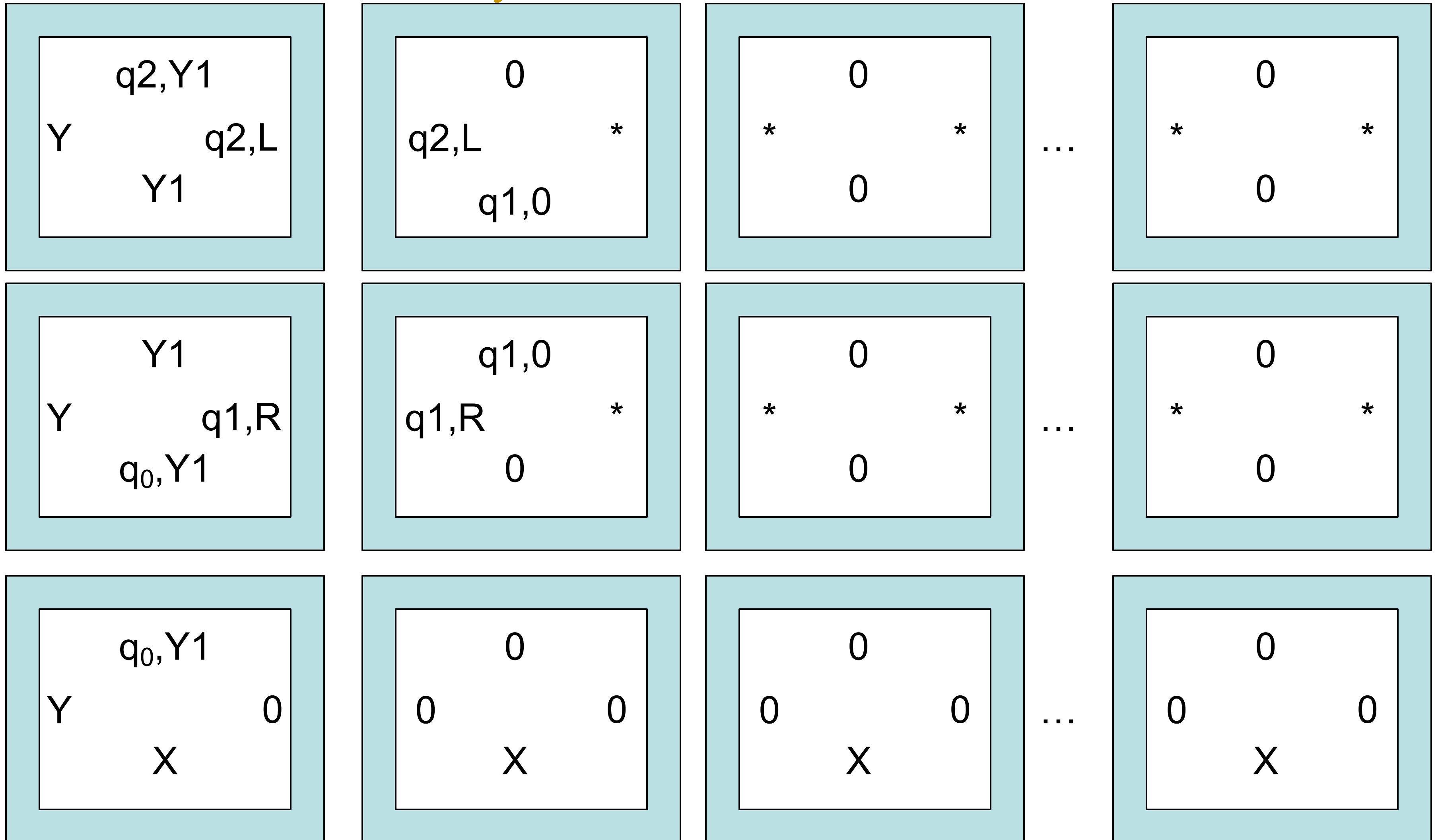
# Sample Starting Rows



# Case 1; Two More Rows





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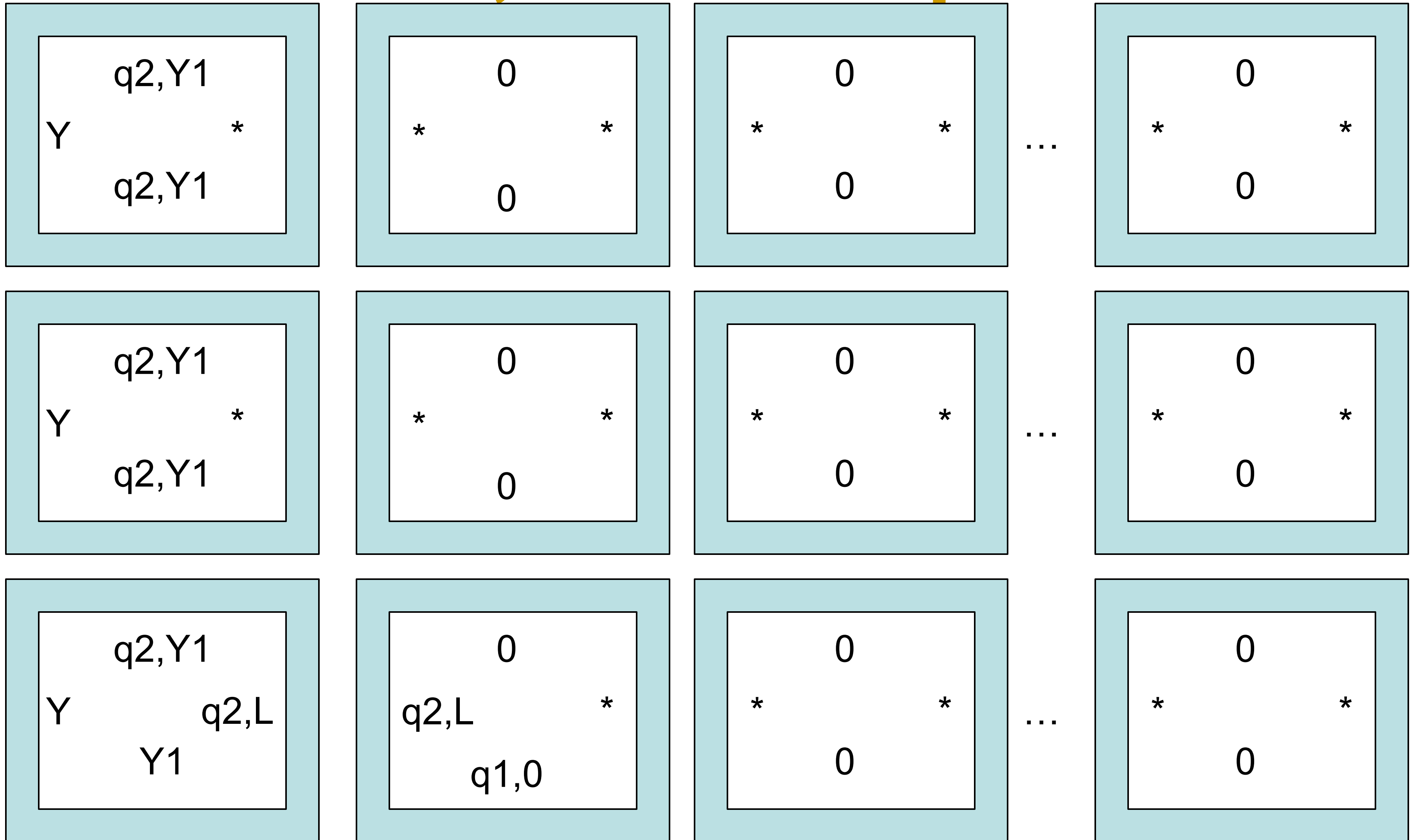
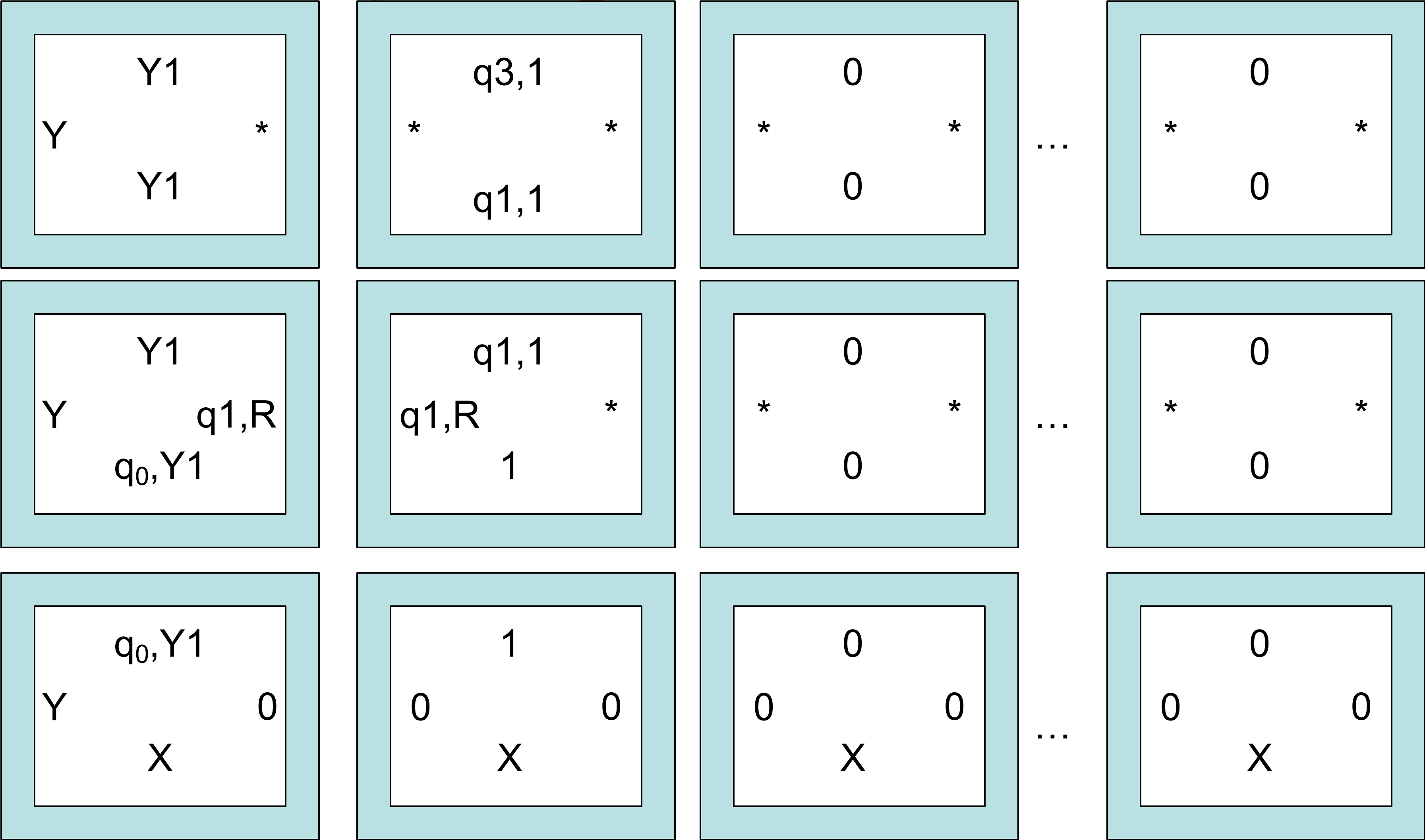
# Case 1; Row 3 repeated



# Case 2; Only Two More Rows



# More on Variations

- One-dimensional space (I asked you to think about that on an earlier slide)

- Infinite 3d space (worse than re/co-re in general)
  - This become a there exists, for all, problem – Does there exist an initial tape for which M never halts
  - In fact, one can mimic acceptance of no inputs here, meaning M is not an algorithm iff we can not tile any of the x-y planes in the 3d space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# PCP Revisited

## Bounded Post Correspondence

# Bounded Variation

- Limit correspondence to a length that is polynomial in **n**, where **n** is length of initial input string.
- Outline of proof we can get for almost free
  - Convert halting problem for a Non-deterministic Turing machine to word problem for a Semi-Thue System
    Note: we originally did for deterministic machines, but the construction works for non-determinism and maps nicely to Semi-Thue systems which are non-deterministic by definition.
  - Recast as an instance of PCP
  - Limit the length of word to $\mathbf{(n+2)^k}$, where original TM accepts or rejects in $\mathbf{n^k}$ steps.


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# Another Approach

- There is a tighter bound on **Bounded PCP**.

- Given sequences **(x1, x2, …, xn)** and **(y1, y2, …, yn)**, and a positive integer
  **K ≤ p(max(|x1|+…+|xn|, |y1|+…+|yn|),**
  where **p** is some polynomial, is there a solution to this instance involving indices **i1, …,ik, k≤K** (not necessarily distinct), of integers between **1** and **n**, such that the corresponding **x** and **y** strings are identical.
- Follows from Constable, Hunt and Sahni (1974). "On the Computational Complexity of Program Scheme Equivalence," *Siam Journal of Computing* 9(2), 396-416.

# Co-NP

## Fourth Significant Class of Problems

# Co–NP

For any decision problem **A** in **NP**, there is a ‘complement’ problem **Co–A** defined on the same instances as **A**, but with a question whose answer is the negation of the answer in **A**. That is, an instance is a "yes" instance for **A** if and only if it is a "no" instance in **Co–A**.

Notice that the complement of the complement of a problem is the original problem.

# GC and Co–GC

**Co–NP** is the set of all decision problems whose complements are members of **NP**.

**Graph Color GC**

Given: A graph **G** and an integer **k**.

Question: Can **G** be properly colored with **k** colors?

**Co–GC**

Given: A graph **G** and an integer **k**.

Question: Do all proper colorings of **G** require <u>more than</u> **k** colors?


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# Co–GC

Notice that **Co–GC** is a problem that does not appear to be in the set **NP**. That is, we know of no way to check in polynomial time the answer to a "Yes" instance of **Co–GC**.

What is the "answer" to a Yes instance that can be verified in polynomial time?


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# P and Co-P

Not all problems in **NP** behave this way. For example, if **X** is a problem in class **P**, then both "yes" and "no" instances can be solved in polynomial time.

That is, both "yes" and "no" instances can be verified in polynomial time and hence, **X** and **Co–X** are both in **NP**, in fact, both are in **P**.

This implies **P** = **Co–P** and, further,

$$\mathbf{P} = \mathbf{Co\text{–}P} \subseteq \mathbf{NP} \cap \mathbf{Co\text{–}NP}.$$


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# Co–NP

This gives rise to a second fundamental question:

**NP = Co-NP?**

If **P = NP**, then **NP = Co-NP.**

This is not "if and only if."

It is possible that **NP = Co-NP** and, yet, **P ≠ NP**.


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# Co–NP Complete

If **A $\leq_P$ B** and both are in **NP**, then the same polynomial transformation will reduce **Co-A** to **Co–B**. That is, **Co–A $\leq_P$ Co–B**. Therefore, **Co–SAT** is 'complete' in **Co–NP**.

In fact, corresponding to **NP–Complete** is the complement set **Co–NP–Complete**, the set of hardest problems in **Co–NP.**

# Turing Reductions

Now, return to **Turing Reductions**.

Recall that **Turing reductions** include polynomial transformations as a special case. So, we should expect they will be more powerful.


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# Turing Reductions

**(**1) Problems **A** and **B** can, but need not, be decision problems.

(2) No restriction placed upon the number of instances of **B** that are constructed.

(3) Nor, how the result, $\mathbf{Answer_A}$, is computed.

In effect, we use an Oracle for **B**.

# NP–Hard

**Fifth Significant Class of Problems**

# NP–Hard

To date, we have concerned ourselves with decision problems. We are now ready to include additional problems, in particular, **optimization** problems.

We require one additional tool – the second type of transformation discussed earlier – **Turing reductions**.

# NP–Hard

Definition: Problem **B** is **NP–Hard** if there is a polynomial time **Turing reduction A** $\leq_{PT}$ **B** for some problem **A** in **NP–Complete**.

This implies **NP–Hard** problems are at least as hard as **NP–Complete** problems. Therefore, they cannot be solved in polynomial time unless **P = NP** (and maybe not then).

This use of an oracle, allows us to reduce **co-NP-Complete** problems to **NP-Complete** ones and vice versa.

# QSAT

- **QSAT** is the problem to determine if an arbitrary fully quantified Boolean expression is true. Note: **SAT** only uses existential.
- **QSAT** is **NP-Hard** but may not be in **NP**.
- **QSAT** can be solved in polynomial space (**PSPACE**).

# NP–Hard

**Polynomial transformations** are **Turing reductions**.

Thus, **NP–Complete** is a subset of **NP–Hard**.

**Co–NP–Complete** also is a subset of **NP–Hard**.

**NP–Hard** contains many other interesting problems.


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# NP-Easy

- **NP-Easy** is the set of function problems that are solvable in polynomial time by a deterministic Turing machine with an oracle for some decision problem in **NP**.
- That is, given an Oracle for some **NP** problem **Y**, if **X** is Turing reducible to **Y** in polynomial time, then **X** is **NP-Easy**.

# NP–Easy

**NP-Easy** problem **X** need not be, but often is, **NP-Complete**.

In fact, **X** can be any problem in **N**P or **Co–NP**.

More to the point, an **NP-Easy** problem does not even need to be a decision problem – it can be an optimization problem or some other problem seeking a numerical rather than binary (yes/no answer).

# NP–Equivalent

Problem **B** in **NP–Hard** is ***NP–Equivalent*** when **B** reduces to some problem **X** in **NP**, That is, **B** $\leq_{PT}$ **X**. This is, when **B** is also **NP-Easy**.

Since **B** is in **NP–Hard**, we already know there is a problem **A** in **NP–Complete** that reduces to **B**. That is, **A** $\leq_{PT}$ **B**.

Since **X** is in **NP**, **X** $\leq_{PT}$ **A**. Therefore, **X** $\leq_{PT}$ **A** $\leq_{PT}$ **B** $\leq_{PT}$ **X**.

Thus, **X**, **A**, and **B** are all polynomially equivalent, and we can say

<u>Theorem.</u> Problems in **NP–Equivalent** are polynomial if and only if **P = NP**.

Example: **Optimization** version of **Subset-Sum** is **NP-Equivalent**.

# NP-Easy and Equivalent

- **NP-Easy** -- these are problems that are polynomial when using an **NP** oracle (**≤pt**)
- **NP-Equivalent** is the class of **NP-Easy** and **NP-Hard** problems (assuming Turing rather than many-one reductions)
  – In essence this is the **functional** equivalent of **NP-Complete** but also of **Co-NP-Complete** since we can negate answers

# Turing vs m-1 Reductions

- In effect, our normal polynomial reduction (**≤p**) is a many-one polynomial time reduction as it just asks and then accepts its oracle’s answer
- In contrast, **NP-Easy** and **NP-Equivalent** employ a Turing machine polynomial time reduction (**≤pt**) that uses rather than mimics answers from its oracle

# SubsetSum Optimization

## NP-Equivalence


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# SubsetSum Optimization (SSO)

**$S = \{s_1, s_2, \ldots, s_n\}$**

set of positive integers

and an integer **B**.

**Optimization:** Find a subset of **S** whose values sum to the largest attainable value **≤B?**

**Strategy:** Use Oracle for **SubsetSum Decision Problem** but only use it a polynomial number of times – Great care must be taken here as **B** takes only **$\log_2$ B** bits to represent

# SSO is NP-Hard

- We can show **SS $\leq_{PT}$ SSO**
- Let **[(s1, s2, …, sn), B]** be an instance of **SubsetSum** (we'll call it **SS**)
- We can ask the oracle for **SSO** for the largest value **G ≤ B** such that some subsequence of **(s1, s2, …, sn)** equals **G**. If its answer is **B** we say "YES"; else we say "NO"

# SSO is NP-Easy

- We can show **SSO $\leq_{PT}$ SubsetSum**
- Let **S = [(s1, s2, …, sn), B]** be an instance of **SSO**
- Again, our goal is to find the largest value **G ≤ B** such that some subsequence of **(s1, s2, …, sn)** equals **G**
- The challenge is to do this in a number of steps that is polynomial in the size of the question. As any integer **k** can be represented in **$\log_2 k$** bits, we need to make sure we don't ask more than **$\log_2 S$** questions of our oracle, where **S** is the length of the representation of **[(s1, s2, …, sn), B]**.
- Read the next slide very carefully

# A Subtle Failure

- Let **[(s1, s2, …, sn), B]** be an instance of **SSO**. Below **sequence A** is **(s1, s2, …, sn)**

```
SUBSET-SUM-OPTIMIZATION(sequence A,  int B) {
    for i=B downto 1
          if ( SubsetSum(A, i) ) then return i;
    return 0;
}
```

- This calls the oracle **SS** up to **B** times
- As **B** is $\mathbf{2^{log2(B)}}$, we might ask an exponential number of questions relative to the representation of our input parameter **B**
- As **B** can be as large as the sum of the sequence **(s1, s2, …, sn**), the value **B** can be exponential in the size of the representation of our input and so our reduction is not polynomially bounded.

# Using SubsetSum Oracle

```
SUBSET-SUM-OPTIMIZATION(sequence A, int B) {
   int best = B;
   for i = floor(log₂B) downto 0 do
      A = A + { 2ⁱ };    // add to multiset;succeeds now
   for i = floor(log₂B) downto 0 do {
      A = A - { 2ⁱ };            // remove from multiset
      if !SUBSET-SUM(A, best) then // 2ⁱ was essential
         best = best - 2ⁱ;  // reduce best
   }
   return best;
}
```

# Example of SubsetSum Opt

- **Initial Values:**
- **A = {1, 4, 5, 7}, best = b = 15**
- **A = {1, 4, 5, 7, 8, 4, 2, 1}, best = 15**
- **A = {1, 4, 5, 7, 4, 2, 1}, best = 15**
- **A = {1, 4, 5, 7, 2, 1}, best = 15**
- **A = {1, 4, 5, 7, 1}, best = 15-2 = 13**
- **A = {1, 4, 5, 7}, best = 13**

# Another Example

- **Initial Values:**
- **A = {1, 4, 5, 7}, best = b = 20**
- **A = {1, 4, 5, 7, 16, 8, 4, 2, 1}, best = 20**
- **A = {1, 4, 5, 7, 8, 4, 2, 1}, best = 20**
- **A = {1, 4, 5, 7, 4, 2, 1}, best = 20**
- **A = {1, 4, 5, 7, 2, 1}, best = 20**
- **A = {1, 4, 5, 7, 1}, best = 20-2 = 18**
- **A = {1, 4, 5, 7}, best = 18-1 = 17**


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# Analysis

- Each loop has **$O(\log_2 B)$** iterations, which is linear with respect to the size of **B**.
- Note that if we tried all values less that B, we would have **O(B)** tries and that is exponential in **$\log_2 B$**, the size of **B**.
- The correct solution takes advantage of the **NP-complete** power of the oracle.

# Minimum Colors for a Graph

- We know K-Color (**KC**) is **NP Complete**
- We can reduce **KC** to **MinColor** problem just by seeing if **MinColor** is **≤ K**. Thus, **MinColor** is **NP-Hard**
- How do we reduce **MinColor** to **KC** asking only a **log** number of questions of the oracle for **KC**?
- Consider, if **N** nodes, then can easily **N-Colo**r
- Can we **N/2-Color**?
  - If so, then try **N/4**
  - If not, then try **3N/4**
- This is a simple binary search for optimal value


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# 2SAT

**A Subset of 3SAT**

**How hard?**


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# 2SAT

- We showed that **3SAT** is **NP Complete**
- What about **2SAT** (two variable per clause)?
- Remember that **2** variables still result in undecidable deducibility from finite axion sets, so we might be suspicious that there are some challenging issues here.


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# Attacking 2SAT

First we need to convert a **2SAT** instance to a different form, the so-called implicative normal form. Note that the expression **a∨b** is equivalent to

**¬a⇒b ∧ ¬b⇒a**

(if one of the two variables is false, then the other one must be true).

We now construct a directed graph of these implications: for each variable x there will be two vertices **x** and **¬x**. The edges will correspond to the implications.

# 2SAT Example

Let's look at an example in 2-CNF form:

**(a V ¬b) Λ (¬a V b) Λ (¬a V ¬b) Λ (a V ¬c)**

The oriented graph will contain the following vertices:

| **(a V ¬b)** | **(¬a V b)** | **(¬a V ¬b)** | **(a V ¬c)** |
|---|---|---|---|
| **¬a⇒¬b** | **a⇒b** | **a⇒¬b** | **¬a⇒¬c** |
| **b⇒a** | **¬b⇒¬a** | **b⇒¬a** | **c⇒a** |


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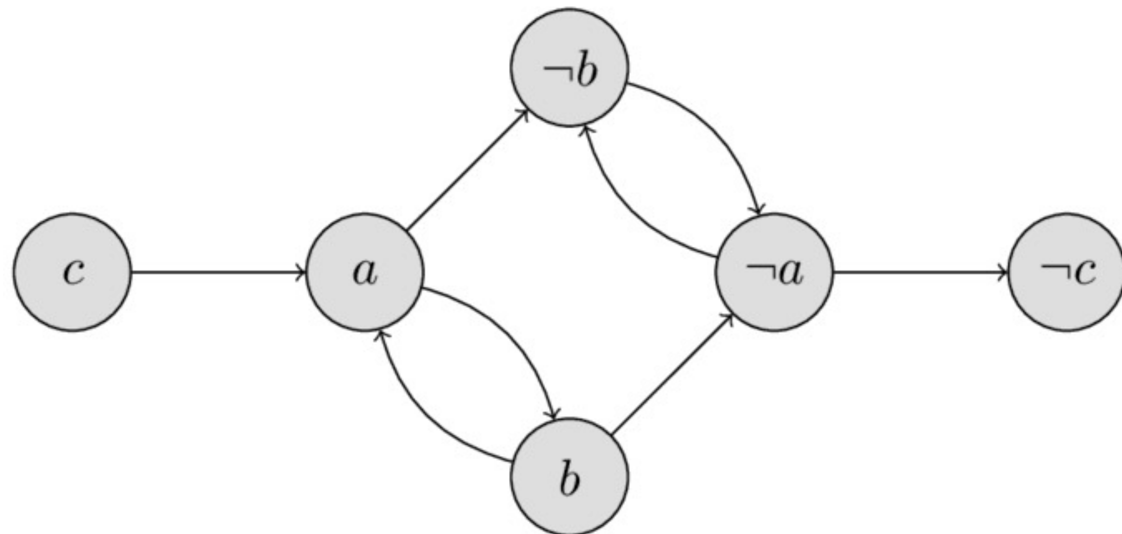
# Graph from 2SAT Example

- If there is an edge **a⇒b**, then there also is an edge **¬b⇒¬a**
- A contradiction exists if there is a cycle, for any variable **x**, that involves **x** and **¬x** (means **x** ⇔ **¬x**, which is a self-contradiction)
- What if there is path from some variable **x** to **¬x** or vice versa?
- **x⇒¬x** can only be satisfied if **x** is false (**¬x true**)





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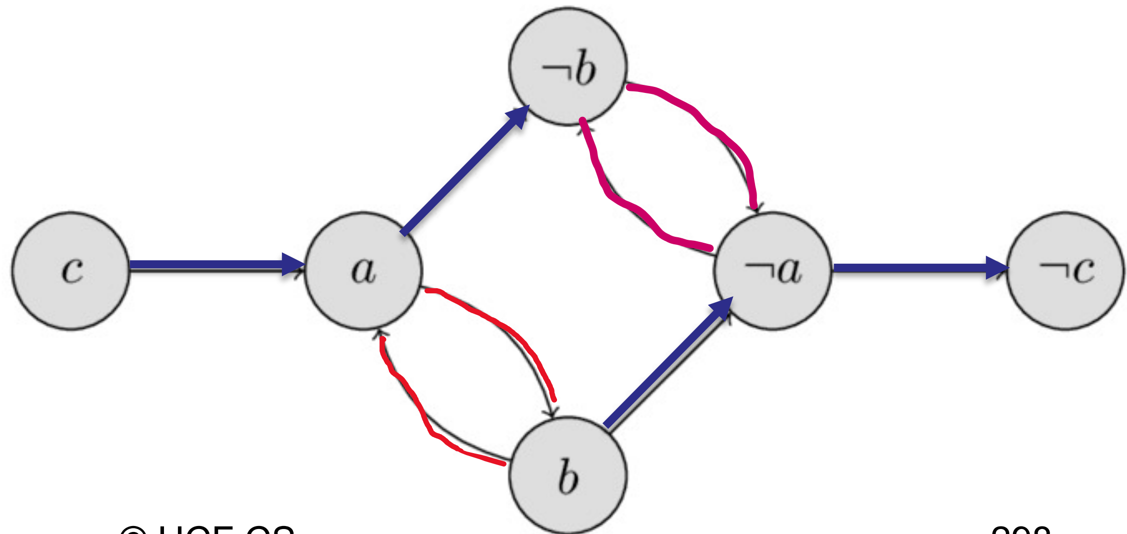
# Finding a Solution for 2SAT

- Looking at our graph, **c** must be false, but so must **a** and **b**, as each has a path to its complement
- Note that, if **a** is true, **b** is true, and if **a** is false, **b** is false
- Fortunately, there are no cycles involving a variable and its complement, so we have a solution **<a = F; b = F; c = F>**
- The trick now is to discover that solution in an algorithmic manner





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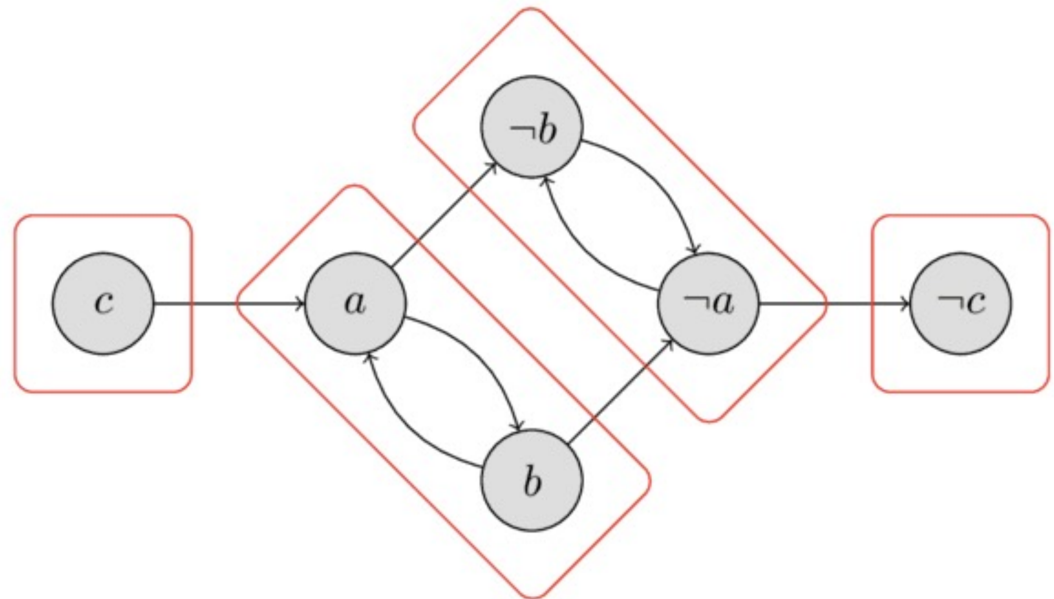
# Strongly Connected Components (SCC)

- A directed graph is strongly connected if there is a path between all pairs of vertices.
- A strongly connected component (**SCC**) of a directed graph is a maximal strongly connected subgraph. For example, there are **4 SCC**s in the graph we have been investigating.





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# Computing SCC

- There are several efficient linear time algorithms for finding the strongly connected components of a graph, based on depth first search
- The one commonly taught in Algorithm Design and Analysis is Tarjan's

# Mapping 2SAT to SCC

- In terms of the implication graph, two literals belong to the same strongly connected component whenever there exist chains of implications from one literal to the other and vice versa.
- Therefore, the two literals must have the same value in any satisfying assignment to the given 2-satisfiability instance. In particular, if a variable and its negation both belong to the same strongly connected component, the instance cannot be satisfied, because it is impossible to assign both these literals the same value.
- This is a necessary and sufficient condition: a **2-CNF** formula is satisfiable if and only if there is no variable that belongs to the same strongly connected component as its negation.


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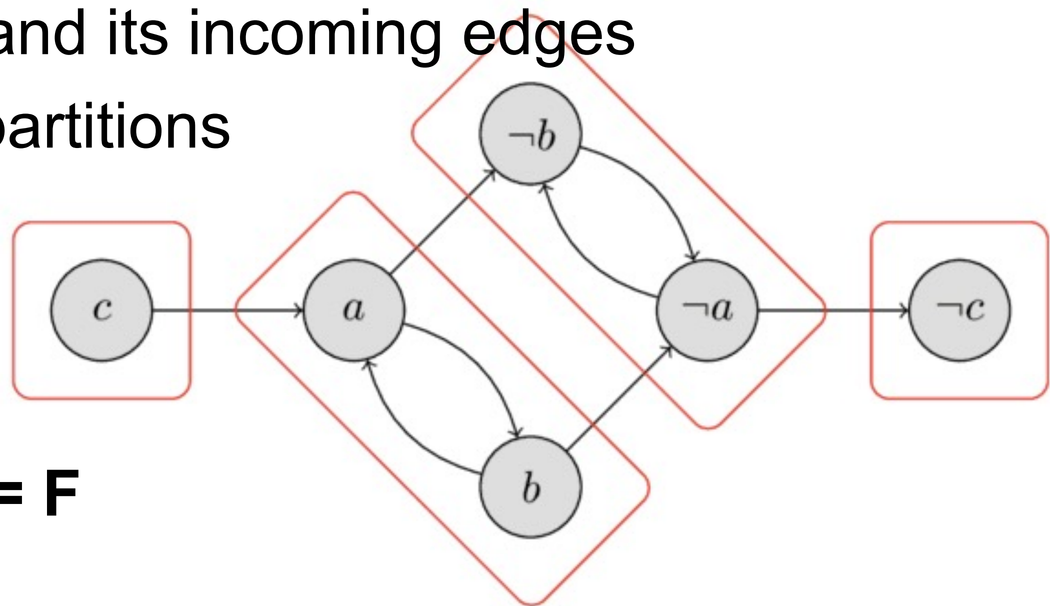
# Solving SCC and 2SAT

- While some variable is not yet assigned
  - Start at a partition that has no outgoing edges
  - Assign **true** to all members of partition
  - Remove partition and its incoming edges
- Can also do **DFS** of partitions
- Either way, we get
  - **¬c = T**
  - **¬a = ¬b = T**
  - And so, **a = b = c = F**





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# Any Hard Problems Here?

- **Minimum-ones 2SAT** problem: Provide a satisfying assignment that sets a minimum number of variables to true.
- **Uniform Min-Ones-2SAT** is the restriction of **Min-Ones-2SAT** to input instances without mixed clauses (must be all positive or all negative literals in each clause)
- **Positive Min-Ones-2SAT** is the restriction of **Uniform Min-Ones-2SAT** to inputs containing only positive clauses (no negations)

# Uniform Min-Ones-2SAT

- **Uniform Min-Ones-2SAT** is **NP-Hard** as we can reduce **Min-Vertex-Cover** to it
- In fact, **Uniform Min-Ones-2SAT** is **NP-Equivalent**
- The best known (to me) uniform minimum-ones **2SAT** problem algorithm has a running time of $\mathbf{O(1.21061^n)}$ on a satisfiable **2SAT** formula with **n** variables


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# Positive Min-Ones-2SAT

- **Positive Min-Ones-2SAT** is also equivalent to **Min-Vertex-Cover** and therefore **NP-Equivalent** as well
- This is interesting as the problem of determining haplotype classifications and propensity for certain genetic diseases can be mapped onto **Positive Min-Ones-2SAT**


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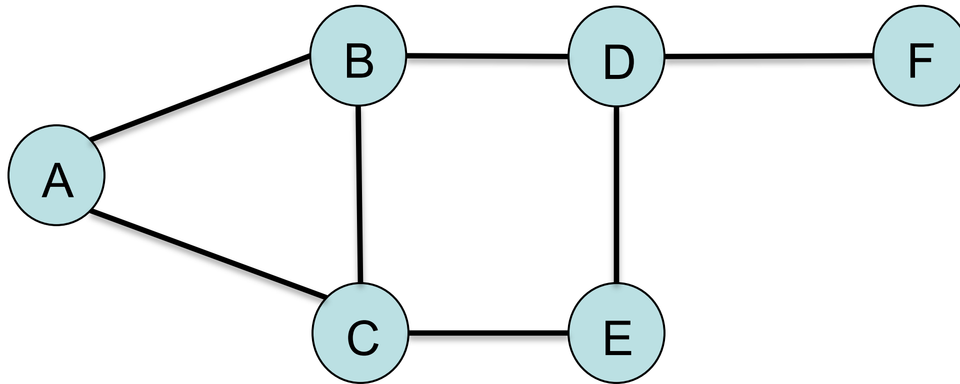
# VC to Positive Min-Ones-2SAT




Can we cover all edges with just **3** vertices?
Recast as Positive Min-Ones-2SAT. Each Node is a variable, each edge is an or (∨). Above is
**(A∨B)(A∨C),(B∨C),(B∨D),(C∨E),(D∨E),(D∨F)**
To answer VC of **3**, ask "is minimum positive assignment **3** or fewer?"
**B,C,D** works and tells us which vertices to choose to **3** cover above
If we added edge between **E** and **F,** the **min** would be **4** and we would require **4** vertices to cover all edges and **4** variables set to true
This shows **Positive Min-Ones-2SAT** is **NP-Hard**

# Positive Min-Ones-2SAT to VC

- Associate every variable with a vertex
- If **(v1$\vee$v2)** is a clause, add an edge between **v1** and **v2** in graph
- Now to find **min**, start with **n/2**, where we have **n** variables and do a binary search for **min** using oracle for **VC**
- Max number of queries of **VC** oracle is just **$\log_2 n$** so this is **NP-Easy** and therefore **NP-Equivalent**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# Finding Triangle Strips

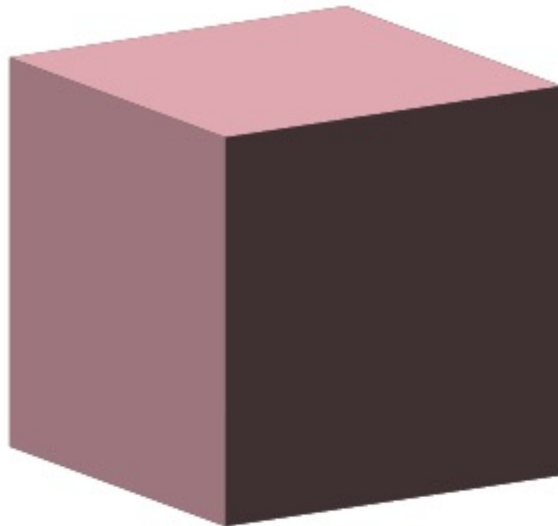
**Adapted from presentation by**
**Ajit Hakke Patil**
**Spring 2010**

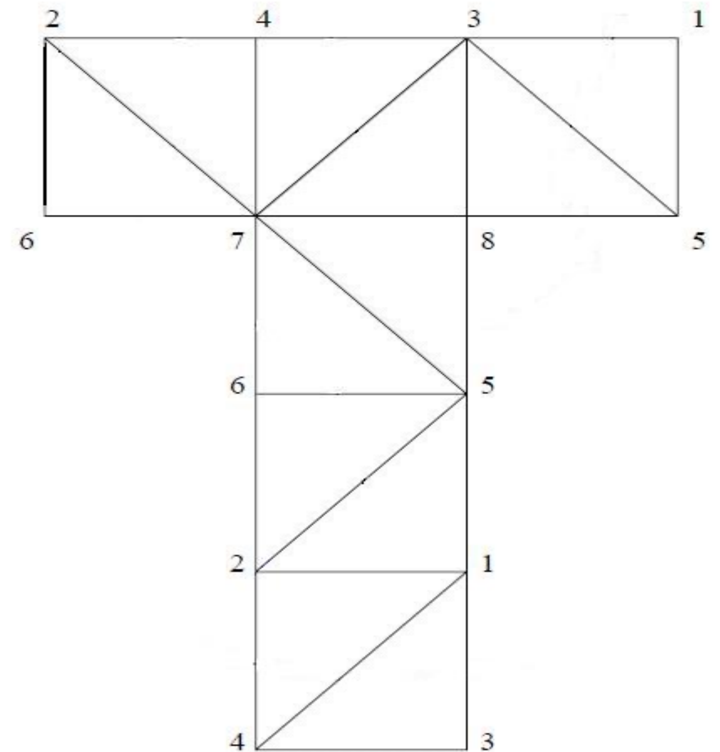
# Graphics Subsystem

- The graphics subsystem (**GS**) receives graphics commands from the application, builds the image specified by the commands, and outputs the resulting image to display hardware
- Graphics Libraries:
  - OpenGL, DirectX.

# Surface Visualization

- As Triangle Mesh
- Generated by triangulating the geometry





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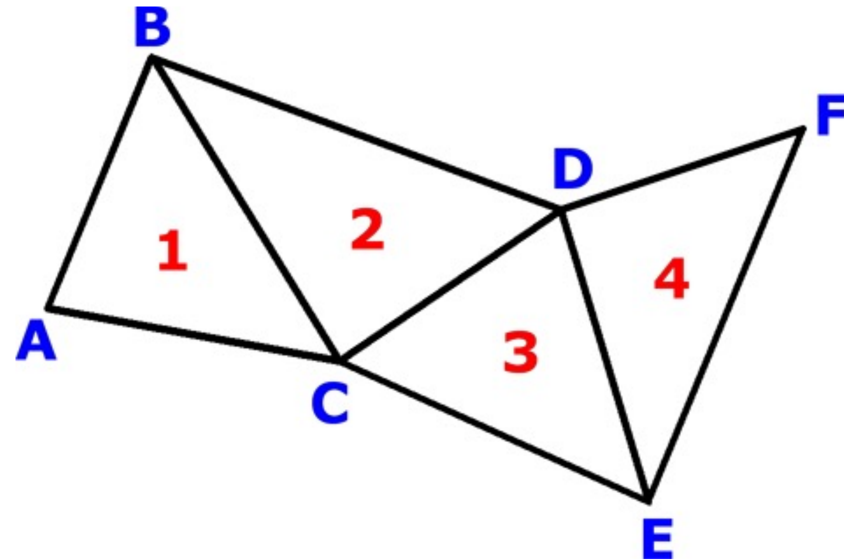
# Triangle List vs Triangle Strip

- **Triangle List**: *Arbitrary ordering of triangles.*
- **Triangle Strip**: *A triangle strip is a sequential ordering of triangles*. i.e consecutive triangles share an edge
- In case of triangle lists we draw each triangle separately.
- So for drawing **N** triangles you need to call/send **3N** vertex drawing commands/data.
- However, using a **Triangle Strip** reduces this requirement from **3N** to **N + 2**, provided a single strip is sufficient.

# Triangle List vs Triangle Strip

- four separate triangles: **ABC**, **CBD**, **CDE**, and **EDF**
- But if we know that it is a triangle strip or if we rearrange the triangles such that it becomes a triangle strip, then we can store it as a sequence of vertices **ABCDEF**
- This sequence would be decoded as a set of triangles **ABC**, **BC**D, **CDE**, and **DEF**
- Storage requirement:
  - **3N => N + 2**





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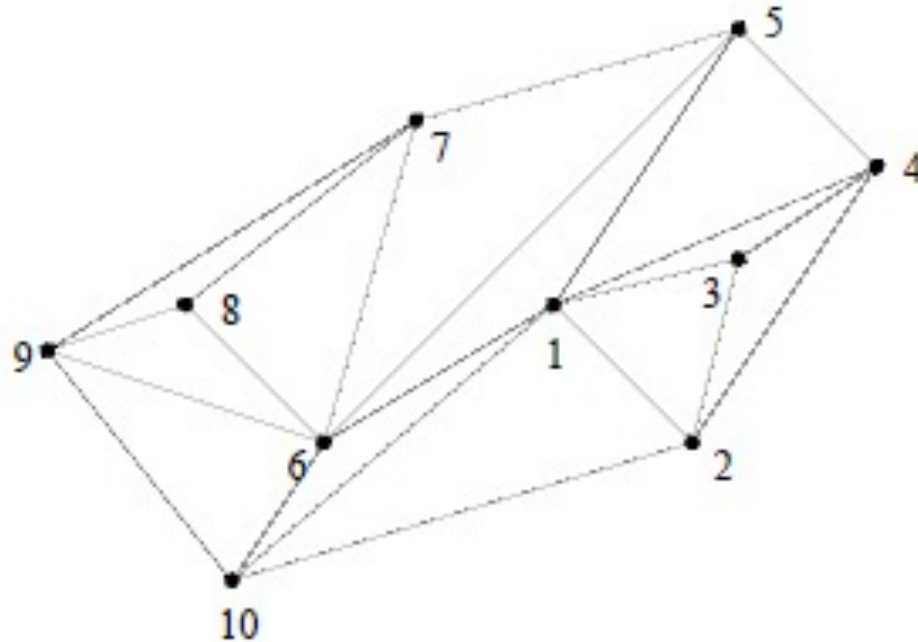
# Tri-strips example

- Single tri-strip that describes triangles is: **1,2,3,4,1,5,6,7,8,9,6,10,1,2**



# K-Stripability

- Given some positive integer **K** (less than the number of triangles).
- Can we create **K** tri-strips for some given triangulation – no repeated triangles.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# Triangle List vs Triangle Strip

```
// Draw Triangle Strip
glBegin(GL_TRIANGLE_STRIP);
 For each Vertex
{
   glVertex3f(x,y,z); //vertex
}
glEnd();
```

```
// Draw Triangle List
glBegin(GL_TRIANGLES);
For each Triangle
{
      glVertex3f(x1,y1,z1);// vertex 1
      glVertex3f(x2,y2,z2);// vertex 2
      glVertex3f(x3,y3,z3);// vertex 3
}
glEnd();
```

# Problem Definition

- Given a triangulation $\mathbf{T = \{t_1, t_2, t_3 ,.. t_n\}}$. Find the **triangle strip** (sequential ordering) for it?
- Converting this to a decision problem.
- Formal Definition:
  Given a triangulation $\mathbf{T = \{t_1, t_2, t_3 ,.. t_N\}}$. Does there exists a **triangle strip**?


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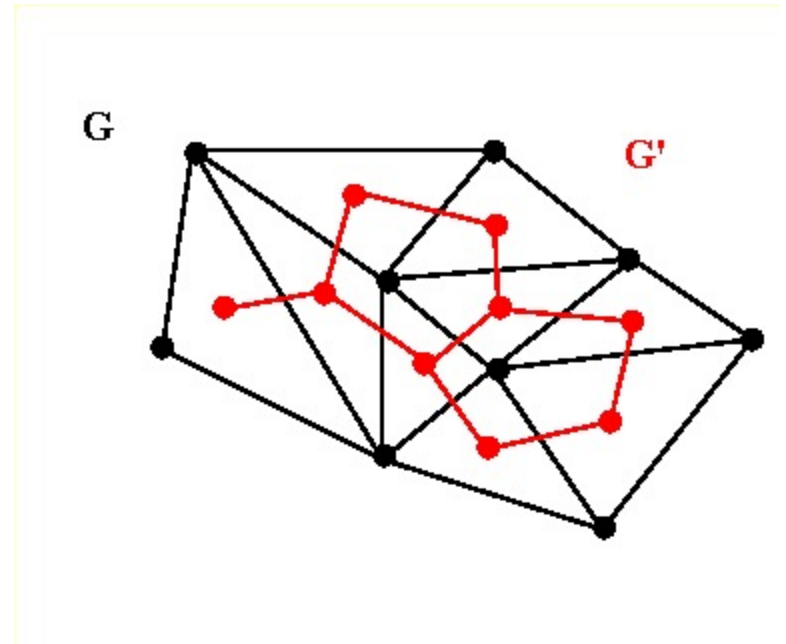
# NP Proof

- Provided a witness of a ‘Yes’ instance of the problem. This must be a sequence of the original triangles where each triangle has a common edge with next one in sequence. We can verify it in polynomial time by checking if the sequential triangles are connected.
- Cost of checking if the consecutive triangles are connected
  - **For i = 1 to N -1**
    - **Check of $i_{th}$ and $i+1_{th}$ triangle are adjacent (have a common edge)**
    - **Up to three edge comparisons or six vertex comparisons**
  - **~ 6N**
- Hence it is in **NP**.

# Dual Graph

- The ***dual graph*** of a triangulation is obtained by defining a vertex for each triangle and drawing an edge between two vertices if their corresponding triangles share an edge
- This gives the triangulations ***edge-adjacency*** in terms of a graph
- Cost of building a **Dual Graph**
  - **$O(N^2)$**
- e.g **G'** is a **dual graph** of **G**.



# NP-Completeness

- To prove it's **NP-Complete** we reduce a known **NP-Complete** problem to this one; the **Hamiltonian Path Problem**.

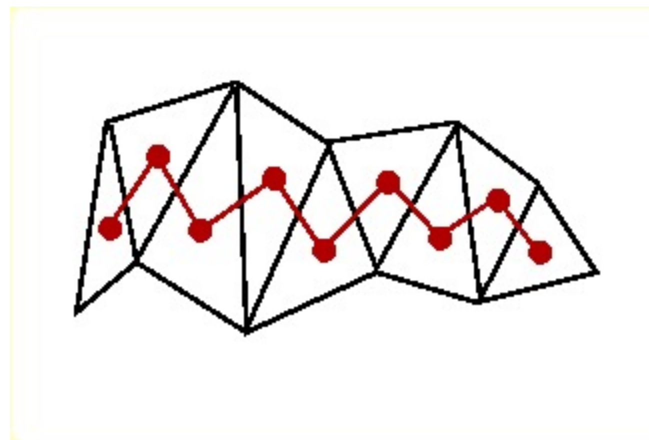
- **Hamiltonian Path Problem**:
  - Given: A **Graph G = (V, E)**. Does **G** contain a path that visits every vertex exactly once?

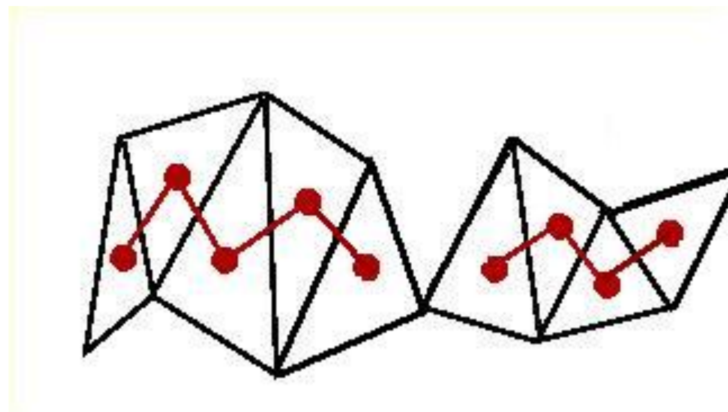
# NP-Completeness proof by restriction

- Accept an Instance of **Hamiltonian Path**, **G = (V, E)**, we restrict this graph to have **max. degree = 3**.The problem is still **NP-Complete**.
- Construct an Instance of **HasTriangleStrip**
  - **G' = G**
    - **V' = V**
    - **E' = E**
  - Let this be the **dual graph G' = (V', E')** of the triangulation **T = {t1, t2, t3 ,.. tN}**.
    - **V'** ~ Vertex $\mathbf{v_i}$ represents triangle $\mathbf{t_i}$, **i = 1 to N**
    - **E'** ~ An edge represents that two triangles are ***edge-adjacent*** (share an edge)
- Return **HasTriangleStrip(T)**

# NP-Completeness

- **G** will have a **Hamiltonian Path** iff **G**’ has one (they are the same).
- **G’** has a **Hamiltonian Path** iff **T** has a triangle strip of length **N – 1**.
- **T** will have a triangle strip of length **N –** 1 iff **G (G’)** has a **Hamiltonian Path**.
- ‘Yes’ instance maps to ‘Yes’ instance. ‘No’ maps to ‘No.’





# HP $\leq_P$ HasTriangleStrip

- The ‘Yes/No’ instance maps to ‘Yes/No’ instance respectively and the transformation runs in polynomial time.
- Polynomial Transformation
- Hence finding **Triangle Strip** in a given triangulation is an **NP-Complete** Problem

# More Complexity Topics

# Weakly NP-Hard/Complete

- Have pseudo polynomial time algorithms – ones that are polynomial in parameter values, rather than size of parameters
- Knapsack is Weakly NP-Hard
- Subset-Sum is Weakly NP-Complete
- A key is that problem is no longer in NP if use unary representation of parameters

# Strongly NP-Hard/Complete

- Do not have pseudo polynomial time algorithms – ones that are polynomial in parameter values, rather than size of parameters
- Bin Packing (scheduling) is Strongly NP-Hard
- A key is that problem remains in NP even if use unary representation of parameters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# PSPACE

- **PSPACE** is set of problems solvable deterministically in polynomial space with unlimited time
  **PSPACE = ∪ SPACE($n^k$)**
- **PSPACE = co-PSPACE = NPSPACE (non-deter, doesn't matter)**
- **PSPACE** is a strict superset of **CSL**s
- **PSPACE-Complete Problem** is, given a regular expression **e** over **Σ**, does **e** denote all strings in **Σ***?
- The above, while solvable, is potentially hard
- Another **PSPACE-Complete** problem is **QSAT**
- **PSPACE** is suspected to outside the **P/NP** hierarchy


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# EXPTIME and EXPSPACE

- **EXPTIME** is the set of problems solvable in $\mathbf{2^{p(n)}}$ on a deterministic TM where is **p** is some polynomial.
- **NEXPTIME** is the set of problems solvable in $\mathbf{2^{p(n)}}$ on a non-deterministic TM.
- **EXPSPACE** is set of problems solvable in $\mathbf{2^{p(n)}}$ space and unbounded time


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# Elementary Functions

$$\text{ELEMENTARY} = \bigcup_{k \in \mathbb{N}} \text{k-EXP}$$
$$= \text{DTIME}(2^n) \cup \text{DTIME}(2^{2^n}) \cup \text{DTIME}(2^{2^{2^n}}) \cup \cdots$$

# Alternating TM (ATM)

- **ATM** adds to **NDTM** notation the notion where, for each state q, q has one of the following properties: (**accept, reject,** $\vee$**,** $\wedge$)
  - $\vee$ means mean accept the string if <u>any</u> final state reached after **q** is accepting
  - $\wedge$ means mean accept the string if <u>all</u> final states reached after **q** are accepting
- **AP = PSPACE** where **AP** is class of problems solvable in polynomial time on an **ATM**

# QSAT, Petri Net, Presburger

- **QSAT** is solvable by an alternating TM in polynomial time and polynomial space
- As noted, before, **QSAT** is **PSPACE-Complete**
- **Petri net reachability** is **EXPSPACE-hard** and requires **2-EXPTIME**
- **Presburger arithmetic** is at least in **2-EXPTIME**, at most in **3-EXPTIME**, and can be solved by an **ATM** with **n** alternating quantifiers in **doubly exponential time**

# Why is Space so Different?

- We made claims that **PSPACE=NPSPACE** even though we cannot show **P = NP**. In fact, we suspect it is not so.
- Savitch's Theorem: **NSPACE(f(n))** $\subseteq$ **DSPACE(f(n)$^2$)**
- This says what we want as, if **f(n)** is a polynomial, then so is **f(n)$^2$**.


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# Key Element of Proof

- If ***L*** is in **NPSPACE(f(n))** then a tree showing the decision process for membership in ***L*** is really a directed graph with $\mathbf{O(2^{f(n)})}$ nodes associated with each of the states that the TM might be in
- For each $\mathbf{x \in \{0,1\}^+}$, $\mathbf{x} \in \boldsymbol{L}$ iff there is a path of from the start configuration to the accepting configuration
- Connectivity from start to accept is what leads to acceptance

# Vertex Connectivity

- In Algorithm Design and Analysis, we focus on time, so long as space is not unreasonable
- We would typically use DFS to determine is a start node **s** has a path to another node **t** in a directed graph **G=(V,E)**
- Time is **O(N)**, **N=|V|+|E|**
- Space is **O(N $lg_2$N)**
- The **$lg_2$N** is for activation records storing node numbers -- there are other things in the activation record, but they have constant size
- We wish to ignore time and do better on size!!!

# Space Complexity of Connectivity

- We can show an **$O((\log_2 n)^2)$**-space deterministic algorithm to decide if there is a path between two vertices in a **directed graph** with **n** vertices
- Key insight is to show we can use a binary search to look for paths of length up to **k**, initially setting **k=n**
- Given **x**, start node **s**, and end node **t**, we check if there is a path from **s** to **t** recursively using a midpoint **u** that is at most **k/2** away from each (binary search)
- This takes **$O(\log_2 n)$** depth (not running time)
- Each recursive call uses **$O(\log_2 n)$** space for stack (activation record: locals + parameters + return address + return value)
- Total space is then **$\log_2 n * \log_2 n = (\log_2 n)^2$**


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# Pseudo Savitch Code

```
Bool k_edge_path (node s, node t, int k) {
    if k == 0 return s == t
    if k == 1 return s == t || (s, t) in edges
    for u in nodes // this introduces O(n) time
        if k_edge_path(s, u, floor(k / 2))
          && k_edge_path(u, t, ceil(k / 2))
            return true
    return false
}
```


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# Getting Back to NPSPACE

- A non-deterministic algorithm using **f(N)** space on any given path has a tree of all paths that has up to $\mathbf{2^{f(N)}}$ nodes
- Based on prior discussion, we can deterministically decide if a starting configuration leads to acceptance in $\mathbf{(\log_2(2^{f(N)}))^2}$-space = $\mathbf{f(N)^2}$-space
- If **f(N)** is a polynomial so is $\mathbf{f(N)^2}$
- Thus, **PSPACE = NPSPACE**


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# Complexity Hierarchy

- **P ⊆ NP ⊆ PSPACE = NPSPACE ⊆ EXPTIME ⊆ NEXPTIME ⊆ EXPSPACE ⊈ 2-EXPTIME ⊈ 3-EXPTIME ⊈ … ⊈ ELEMENTARY ⊈ PRF ⊈ REC**
- What if **P ≠ EXPTIME**; At least one of these is true
  - **P ⊈ NP**
  - **NP ⊈ PSPACE**
  - **PSPACE ⊈ EXPTIME**
- If **NP ≠ NEXPTIME**; At least of these is true
  - **NP ⊈ PSPACE**
  - **PSPACE ⊈ EXPTIME**
  - **EXPTIME ⊈ NEXPTIME**
    - Note that **EXPTIME = NEXPTIME iff P=NP**
    - Note that **k-EXPTIME ⊈ (k+1)-EXPTIME, k>0**
- What If **PSPACE ≠ EXPSPACE**; At least one of these is true
  - **PSPACE ⊈ EXPTIME**
  - **EXPTIME ⊈ EXPSPACE**

# FP and FNP

- **FP** is functional equivalent to **P**
  **R(x,y)** in **FP** if can provide value **y** for input **x** via a deterministic polynomial time algorithm
- **FNP** is functional equivalent to **NP**;
  **R(x,y)** in **FNP** if can verify any pair **(x,y)** via a non-deterministic polynomial time algorithm


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# TFNP

- **TFNP** is the subset of **FNP** where a solution always exists, i.e., there is a **y** for each **x** such that **R(x,y)**.
  - Task of a **TFNP** algorithm is to find a **y**, given **x**, such that **R(x,y)**
  - Unlike **FNP**, the search for a **y** is always successful
- **FNP** properly contains **TFNP** contains **FP** (we don't know if proper)


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# Prime Factoring

- **Prime factoring** is defined as, given **n** and **k**, does **n** have a prime factor **< k**?
- Factoring is in **NP** and **co-NP**
  - Given candidate factor can check its primality in poly time and then see if it divides **n**
  - Given candidate set of factors can check their primalities, and see if product equals **n**; if so, and no candidate **< k**, then answer is no

# Prime Factoring and TFNP

- **Prime Factoring** as a **functional problem** is in **TFNP**, but is it in **FP?**
- If **TFNP** in **FP,** then **TFNP = FP** since **FP** contained in **TFNP**
- If that is so, then carrying out **Prime Factoring** is in **FP** and its decision problem is in **P**
  - If this is so, we must fear for encryption techniques, most of which depends on difficulty of finding factors of a large number

# More TFNP

- There is no known recursive enumeration of **TFNP** but there is of **FNP**
  - This is similar to total versus partially recursive functions (analogies are everywhere)
- It appears that **TFNP** does not have any complete problems!!!
  - But there are subclasses of **TFNP** that do have complete problems!!


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# Another Possible Analogy

- Is **P = (NP ∩ Co-NP)?**
- Recall that **REC = (RE ∩ co-RE)**
- The analogous result may not hold here

# Khot's Conjecture

- It starts with a Graph, **G**, and some set of colors, often many more than needed to properly color **G**, and some added pairwise constraints, e.g., if we color a node red, all adjacent nodes must be green.
- Assuming we have some finite large set of these pairwise constraints, and we know that there is some coloring of **G** that satisfies **99%** of them, then find a coloring that satisfies just **1%** is hard (**NP-Hard**)
- In fact, if **x** is a large percentage, even **99.999%**, then this applies to finding a coloring that satisfies just **0.001%** of the constraints (lots of constraint options here)


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# Is Khot's Conjecture True?

- **FALSE**: If the constraints can be mostly satisfied, all known cases have easy solutions to check satisfaction of some small number of constraints. Also, a large subset of these problems were shown not to require exponential time.
- **TRUE**: Recent results show that, if our constraints give us two color choices for neighbors, not just one, then the problem is **NP-Hard**. This can be extended to show that if there is a solution for almost half the constraints, then the problem is **NP-Hard** to satisfy a small percentage of the constraints. That's nice but does it apply when we start by having almost all constraints satisfiable by some coloring?? It does, however, provide tantalizing evidence in support of **Khot's Conjecture**.


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# Why Do We Care

- It is in the intersection of **Khot's Conjecture** and the question as to whether **P ≠ NP** where things get really interesting
- Specifically, if **Khot's conjecture** is true and **P ≠ NP**, then **NP-Hard** problems not only require exponential time but also it will be the case that getting good, generally applicable, polynomial-time approximations is out of our reach


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