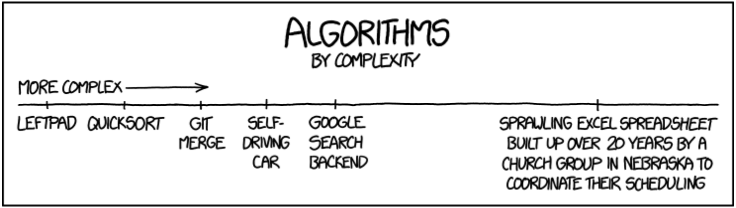
NP and Computational Intractability

T. M. Murali

November 7, 12, 2018

Algorithm Design



- Patterns
  - Greed. $O(n \log n)$ interval scheduling.
  - Divide-and-conquer. $O(n \log n)$ closest pair of points.
  - Dynamic programming. $O(n^3)$ RNA folding.
  - Duality. $O(nm^2)$ maximum flow and minimum cuts.

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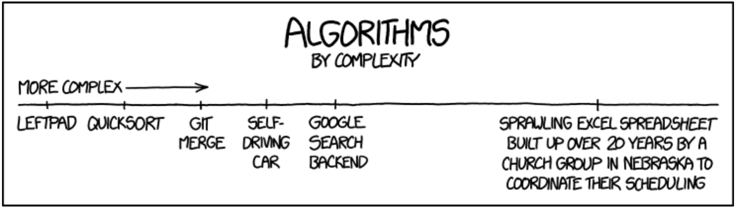

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  - Reductions. Image segmentation $\leq_P$ Minimum s-t cut
  - Local search.
  - Randomization.

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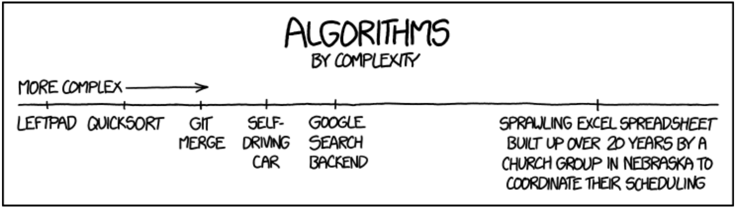

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  - Reductions. IMAGE SEGMENTATION $\leq_P$ MINIMUM s-t CUT
  - Local search.
  - Randomization.
- "Anti-patterns"
  - NP-completeness. $O(n^k)$ algorithm unlikely.
  - PSPACE-completeness. $O(n^k)$ certification algorithm unlikely.
  - Undecidability. No algorithm possible.

Computational Tractability

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Polynomial time	**Probably not**
Shortest path	Longest path
Matching	3-D matching
Minimum cut	Maximum cut
2-SAT	3-SAT
Planar four-colour	Planar three-colour
Bipartite vertex cover	Vertex cover
Primality testing	Factoring

Problem Classification

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- Some extremely hard problems cannot be solved efficiently (e.g., chess on an n-by-n board).
- However, classification is unclear for a very large number of discrete computational problems.
- We can prove that these problems are fundamentally equivalent and are manifestations of the same problem!

Polynomial-Time Reduction

- Goal is to express statements of the type "Problem X is at least as hard as problem Y."
- Use the notion of *reductions*.
- *Y is polynomial-time reducible to X ($Y \leq_P X$)*

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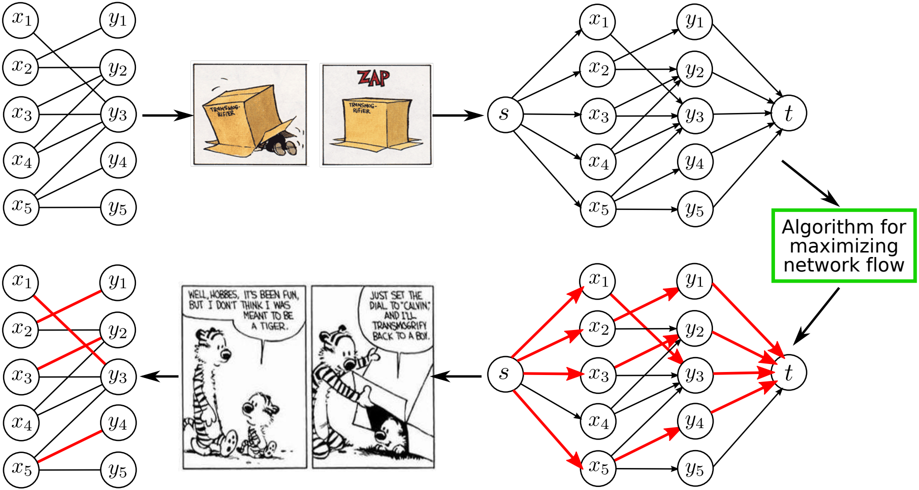
Polynomial-Time Reduction



MAXIMUM BIPARTITE MATCHING $\leq_P$ MAXIMUM s-t FLOW

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  - MAXIMUM BIPARTITE MATCHING $\leq_P$ MAXIMUM s-t FLOW
  - IMAGE SEGMENTATION $\leq_P$ MINIMUM s-t CUT
- $Y \leq_P X$ implies that "X is at least as hard as Y."
- Such reductions are *Karp reductions*. *Cook reductions* allow a polynomial number of calls to the black box that solves X.

Usefulness of Reductions

- Claim: If $Y \leq_P X$ and X can be solved in polynomial time, then Y can be solved in polynomial time.

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- Claim: If $Y \leq_P X$ and X can be solved in polynomial time, then Y can be solved in polynomial time.
- Contrapositive: If $Y \leq_P X$ and Y cannot be solved in polynomial time, then X cannot be solved in polynomial time.
- Informally: If Y is hard, and we can show that Y reduces to X, then the hardness "spreads" to X.

Reduction Strategies

- Simple equivalence.
- Special case to general case.
- Encoding with gadgets.

Optimisation versus Decision Problems

- So far, we have developed algorithms that solve optimisation problems.
  - Compute the *largest* flow.
  - Find the *closest* pair of points.
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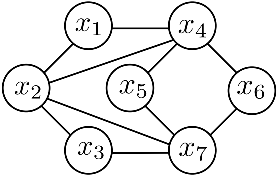
- So far, we have developed algorithms that solve optimisation problems.
  - Compute the *largest* flow.
  - Find the *closest* pair of points.
  - Find the schedule with the *least* completion time.
- Now, we will focus on *decision versions* of problems, e.g., is there a flow with value at least k, for a given value of k?
- Decision problem: answer to every input is `yes` or `no`.

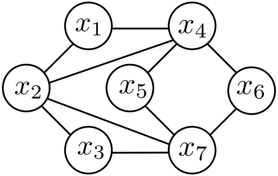
PRIMES

INSTANCE: A natural number n

QUESTION: Is n prime?

Independent Set and Vertex Cover





- Given an undirected graph $G(V, E)$, a subset $S \subseteq V$ is an *independent set* if no two vertices in S are connected by an edge.
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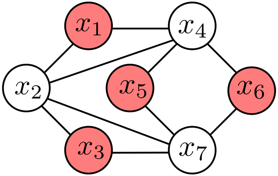

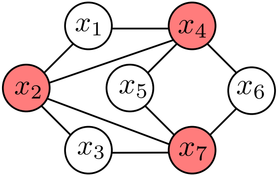

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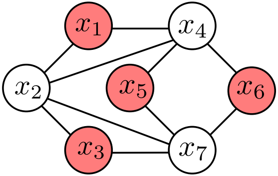

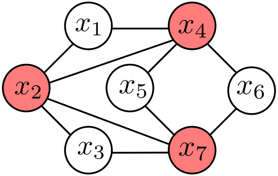

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INDEPENDENT SET

INSTANCE: Undirected graph G and an integer k

QUESTION: Does G contain an independent set of size $\geq k$?

VERTEX COVER

INSTANCE: Undirected graph G and an integer l

QUESTION: Does G contain a vertex cover of size $\leq l$?

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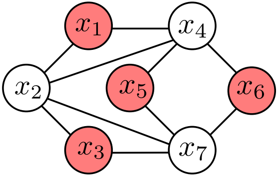

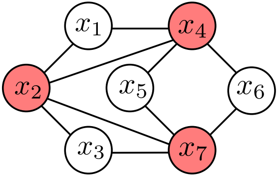

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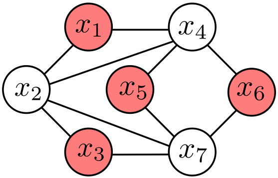

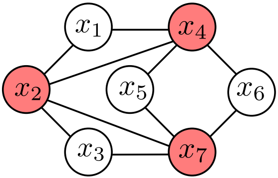

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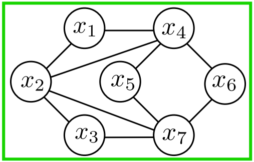
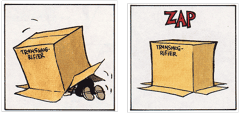
- Demonstrate simple equivalence between these two problems.
- Claim: INDEPENDENT SET $\leq_P$ VERTEX COVER and VERTEX COVER $\leq_P$ INDEPENDENT SET.

Strategy for Proving Indep. Set $\leq_P$ Vertex Cover

$k = 3$





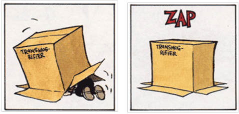
$l = ?$

Input graph for the vertex cover problem

Black box algorithm for solving vertex cover

Yes

No

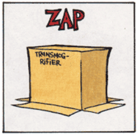


Yes, there is an independent set of size at least 3

No, every independent set is of size 3 or less

Strategy for Proving Indep. Set $\leq_P$ Vertex Cover

1. Start with an arbitrary instance of INDEPENDENT SET: an undirected graph $G(V, E)$ and an integer k.
2. From $G(V, E)$ and k, create an instance of VERTEX COVER: an undirected graph $G'(V', E')$ and an integer l.
   - G' related to G in some way.
   - l can depend upon k and size of G.



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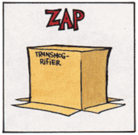

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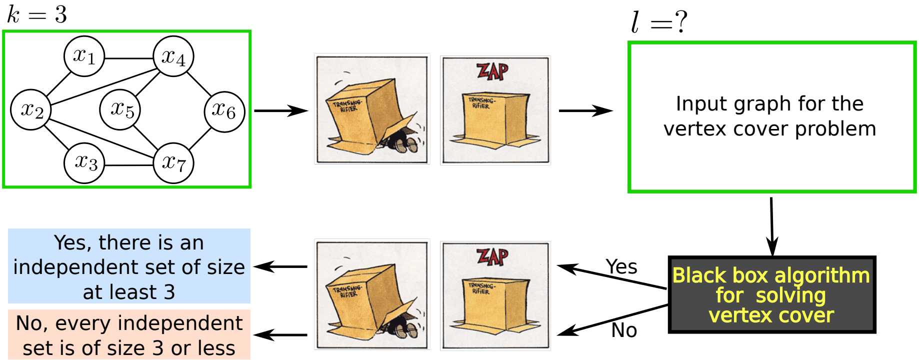
- Transformation and proof must be correct for all possible graphs $G(V, E)$ and all possible values of k.
- Why is the proof an iff statement?

Reason for Two-Way Proof



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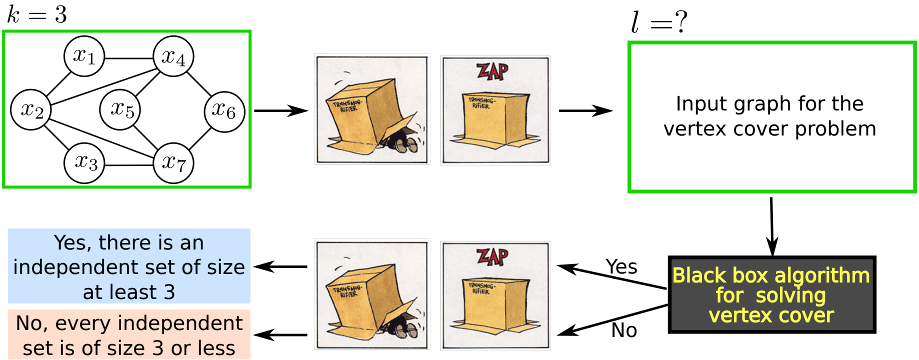
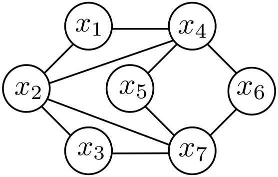
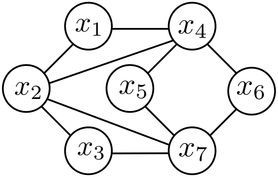


- Why is the proof an iff statement? In the reduction, we are using black box for VERTEX COVER to solve INDEPENDENT SET.
  1. If there is an independent set size $\geq k$, we must be sure that there is a vertex cover of size $\leq l$, so that we know that the black box will find this vertex cover.
  2. If the black box finds a vertex cover of size $\leq l$, we must be sure we can construct an independent set of size $\geq k$ from this vertex cover.

Proof that Independent Set $\leq_P$ Vertex Cover





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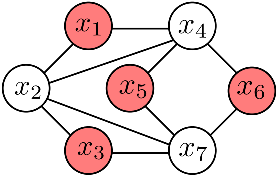

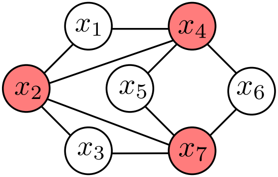

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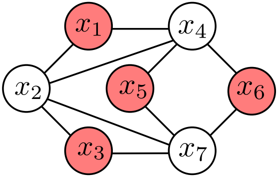

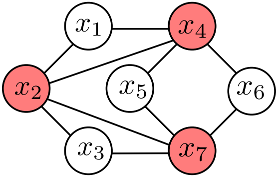

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- Same idea proves that VERTEX COVER $\leq_P$ INDEPENDENT SET

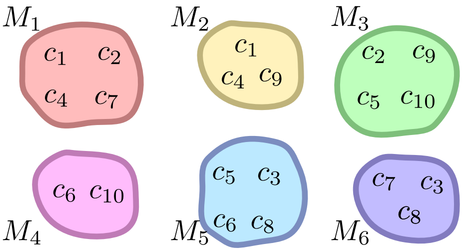
Vertex Cover and Set Cover

- INDEPENDENT SET is a "packing" problem: pack as many vertices as possible, subject to constraints (the edges).
- VERTEX COVER is a "covering" problem: cover all edges in the graph with as few vertices as possible.
- There are more general covering problems.

MICROBE COVER

INSTANCE: A set U of n compounds, a collection $M_1, M_2, \ldots, M_l$ of microbes, where each microbe can make a subset of compounds in U, and an integer k.

QUESTION: Is there a subset of $\leq k$ microbes that can together make all the compounds in U?



$n = 10, l = 6$

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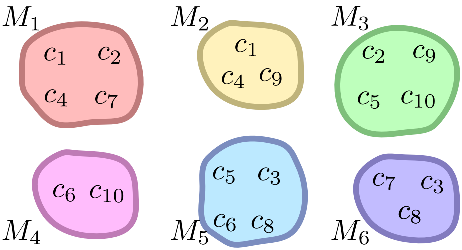

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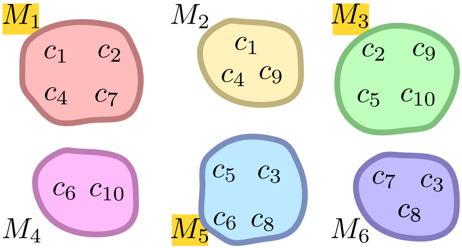
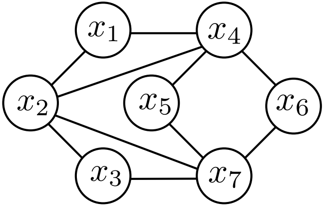


$n = 10, l = 6, k = 3$

Vertex Cover $\leq_P$ Microbe Cover



- Input to VERTEX COVER: an undirected graph $G(V, E)$ and an integer k.
- Let $|V| = l$.
- Create an instance $\{U, \{M_1, M_2, \ldots M_l\}\}$ of MICROBE COVER where

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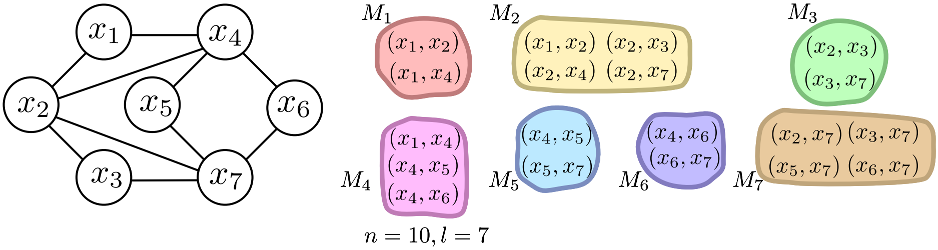

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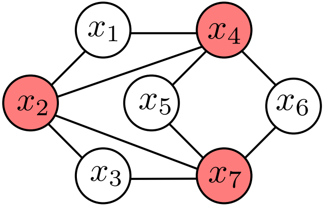

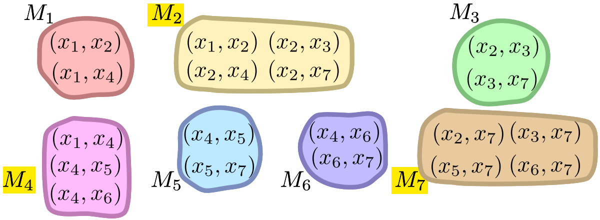

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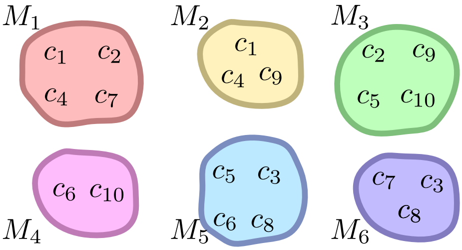
  - for each node $i \in V$, create a microbe M_i whose compounds are the set of edges incident on i.
- Claim: U can be covered with $\leq k$ microbes iff G has a vertex cover with at $\leq k$ nodes.
- Proof strategy:
  1. If G has a vertex cover of size $\leq k$, then U can be covered with $\leq k$ microbes.
  2. If U can be covered with $\leq k$ microbes, then G has a vertex cover of size $\leq k$.

Microbe Cover and Set Cover

Microbe Cover

INSTANCE: A set U of n compounds, a collection $M_1, M_2, \ldots, M_l$ of microbes, where each microbe can make a subset of compounds in U, and an integer k.

QUESTION: Is there a subset of $\leq k$ microbes that can together make all the compounds in U?



$n = 10, l = 6$

- Purely combinatorial problem: a "microbe" is just a set of "compounds."

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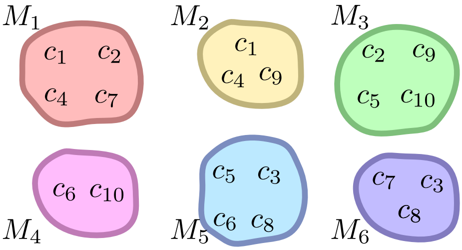

$n = 10, l = 6$

- Purely combinatorial problem: a "microbe" is just a set of "compounds."

SET COVER

INSTANCE: A set U of n elements, a collection $S_1, S_2, \ldots, S_m$ of subsets of U, and an integer k.

QUESTION: Is there a collection of $\leq k$ sets in the collection whose union is U?

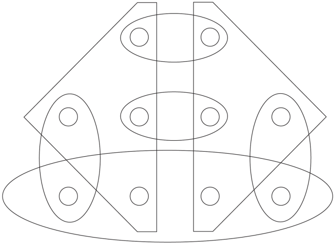

Figure 8.2 An instance of the Set Cover Problem.

Boolean Satisfiability

- Abstract problems formulated in Boolean notation.

Boolean Satisfiability

- Abstract problems formulated in Boolean notation.
- Given a set $X = \{x_1, x_2, \ldots, x_n\}$ of n Boolean variables.
- Each variable can take the value 0 or 1.
- *Term*: a variable x_i or its negation $\overline{x_i}$.
- *Clause* of *length* l: (`or`) of l distinct terms $t_1 \vee t_2 \vee \cdots t_l$.
- *Truth assignment* for X: is a function $\nu : X \to \{0, 1\}$.
- An assignment ν *satisfies* a clause C if it causes at least one term in C to evaluate to 1 (since C is an `or` of terms).
- An assignment *satisfies* a collection of clauses $C_1, C_2, \ldots C_k$ if it causes all clauses to evaluate to 1, i.e., $C_1 \wedge C_2 \wedge \cdots C_k = 1$.
  - ν is a *satisfying assignment* with respect to $C_1, C_2, \ldots C_k$.
  - set of clauses $C_1, C_2, \ldots C_k$ is *satisfiable*.

Example

- $X = \{x_1, x_2, x_3, x_4\}$
- Terms: $x_1, \overline{x_1}, x_2, \overline{x_2}, x_3, \overline{x_3}, x_4, \overline{x_4}$

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$$x_1 \vee \overline{x_2} \vee \overline{x_3}$$
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- Assignment: $x_1 = 1, x_2 = 0, x_3 = 1, x_4 = 0$

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SAT and 3-SAT

SATISFIABILITY PROBLEM (SAT)

INSTANCE: A set of clauses $C_1, C_2, \ldots C_k$ over a set $X = \{x_1, x_2, \ldots x_n\}$ of n variables.

QUESTION: Is there a satisfying truth assignment for X with respect to C?

SAT and 3-SAT

3-Satisfiability Problem (SAT)

INSTANCE: A set of clauses $C_1, C_2, \ldots C_k$, each of length three, over a set $X = \{x_1, x_2, \ldots x_n\}$ of n variables.

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SAT and 3-SAT

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QUESTION: Is there a satisfying truth assignment for X with respect to C?

- SAT and 3-SAT are fundamental combinatorial search problems.
- We have to make n independent decisions (the assignments for each variable) while satisfying a set of constraints.
- Satisfying each constraint in isolation is easy, but we have to make our decisions so that all constraints are satisfied simultaneously.

Examples of 3-SAT

Example:

- $C_1 = x_1 \vee 0 \vee 0$
- $C_2 = x_2 \vee 0 \vee 0$
- $C_3 = \overline{x_1} \vee \overline{x_2} \vee 0$

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3. Is $C_2 \wedge C_3$ satisfiable?

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4. Is $C_1 \wedge C_2 \wedge C_3$ satisfiable?

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4. Is $C_1 \wedge C_2 \wedge C_3$ satisfiable? No.

3-SAT and Independent Set

$C_1 = x_1 \vee \overline{x_2} \vee \overline{x_3}$

$C_2 = \overline{x_1} \vee x_2 \vee x_4$

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- We want to prove 3-SAT $\leq_P$ Independent Set.

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- Two ways to think about 3-SAT:
  1. Make an independent 0/1 decision on each variable and succeed if we achieve one of three ways in which to satisfy each clause.

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- Two ways to think about 3-SAT:
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1. Select $x_1 = 1, x_2 = 1, x_3 = 1, x_4 = 1$.
2. Choose one literal from each clause to evaluate to true.
   - Choices of selected literals imply $x_1 = 0, x_2 = 0, x_4 = 1$.

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- We are given an instance of 3-SAT with k clauses of length three over n variables.
- Construct an instance of independent set: graph $G(V, E)$ with $3k$ nodes.

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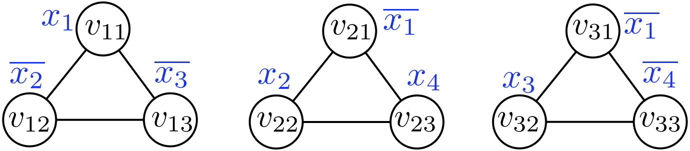

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  - For each clause $C_i, 1 \leq i \leq k$, add a triangle of three nodes v_{i1}, v_{i2}, v_{i3} and three edges to G.
  - Label each node $v_{ij}, 1 \leq j \leq 3$ with the jth term in C_i.

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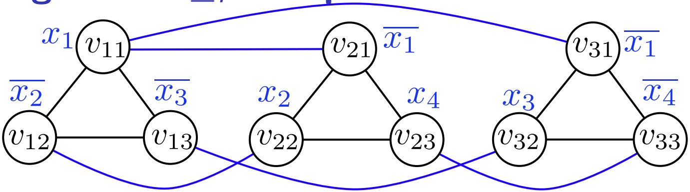

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  - Add an edge between each pair of nodes whose labels correspond to terms that conflict.

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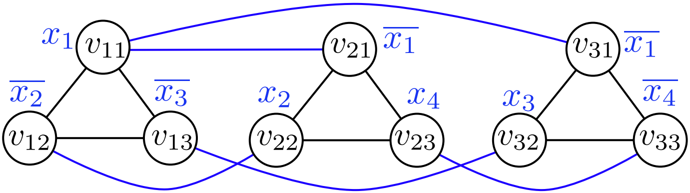

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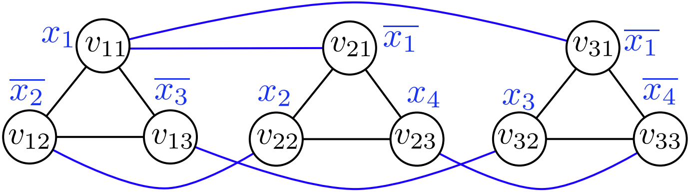

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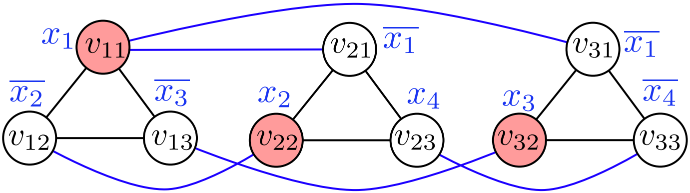

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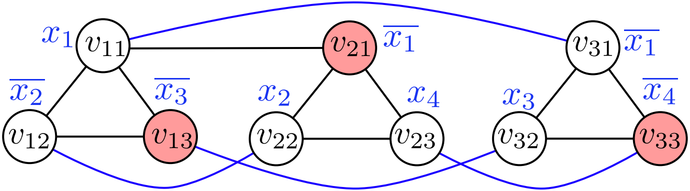

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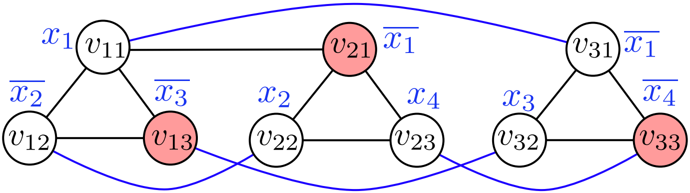

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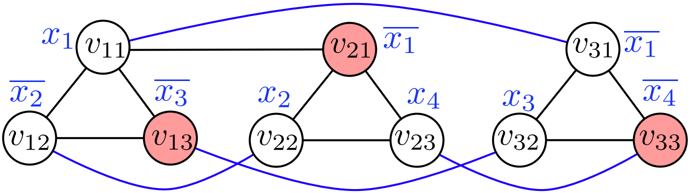

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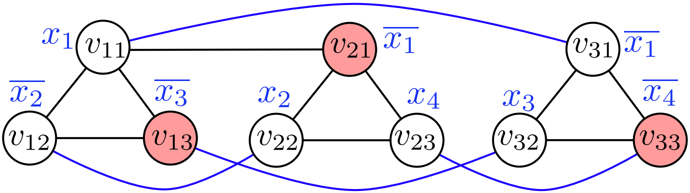

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  - For each variable x_i, only x_i or $\overline{x_i}$ is the label of a node in S. Why?
  - If x_i is the label of a node in S, set $x_i = 1$; else set $x_i = 0$.
  - Why is each clause satisfied?

Transitivity of Reductions

- Claim: If $\mathrm{Z} \leq_P \mathrm{Y}$ and $\mathrm{Y} \leq_P \mathrm{X}$, then $\mathrm{Z} \leq_P \mathrm{X}$.

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- We have shown

$$\text{3-SAT} \leq_P \textsc{Independent Set} \leq_P \textsc{Vertex Cover} \leq_P \textsc{Set Cover}$$

Finding vs. Certifying

- Is it easy to check if a given set of vertices in an undirected graph forms an independent set of size at least k?
- Is it easy to check if a particular truth assignment satisfies a set of clauses?

Finding vs. Certifying

- Is it easy to check if a given set of vertices in an undirected graph forms an independent set of size at least k?
- Is it easy to check if a particular truth assignment satisfies a set of clauses?
- We draw a contrast between *finding* a solution and *checking* a solution (in polynomial time).
- Since we have not been able to develop efficient algorithms to solve many decision problems, let us turn our attention to whether we can check if a proposed solution is correct.

Problems and Algorithms

PRIMES
INSTANCE: A natural number n
QUESTION: Is n prime?

- Decision problem X: for every input s, answer $X(s)$ is `yes` or `no`.

Problems and Algorithms

PRIMES
INSTANCE: A natural number n
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- Decision problem X: for every input s, answer $X(s)$ is $\texttt{yes}$ or $\texttt{no}$.
- An algorithm A for a decision problem receives an input s and returns $A(s) \in \{\texttt{yes}, \texttt{no}\}$.
- An algorithm A *solves* the problem X if for every input s,
  - if $X(s) = \texttt{yes}$ then $A(s) = \texttt{yes}$ and
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Problems and Algorithms

PRIMES
INSTANCE: A natural number n
QUESTION: Is n prime?

- Decision problem X: for every input s, answer $X(s)$ is $\texttt{yes}$ or $\texttt{no}$.
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- A has a *polynomial running time* if there is a polynomial function $p(\cdot)$ such that for every input s, A terminates on s in at most $O(p(|s|))$ steps.
  - There is an algorithm such that $p(|s|) = |s|^{12}$ for PRIMES (Agarwal, Kayal, Saxena, 2002, improved to $|s|^6$ by Pomerance and Lenstra, 2005).

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A decision problem X is in $\mathcal{P}$ iff there is an algorithm A with polynomial running time that solves X.

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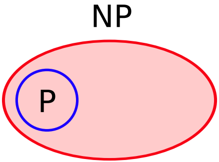

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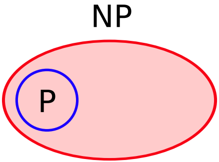

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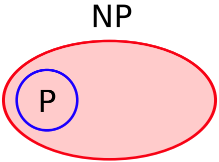

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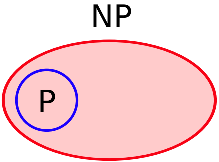

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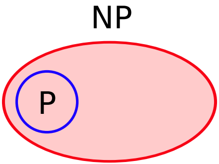
Summary



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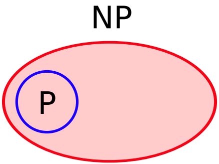

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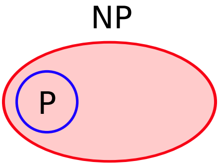

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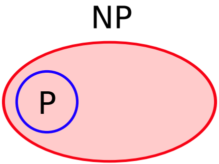

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$\mathcal{NP}$-Complete and $\mathcal{NP}$-Hard Problems

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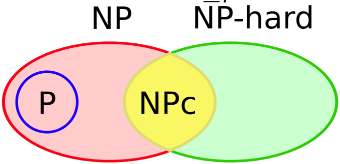

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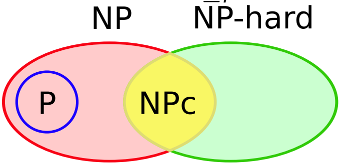

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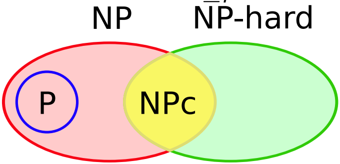

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- Does even one $\mathcal{NP}$-Complete problem exist?! If it does, how can we prove that *every* problem in $\mathcal{NP}$ reduces to this problem?

Circuit Satisfiability

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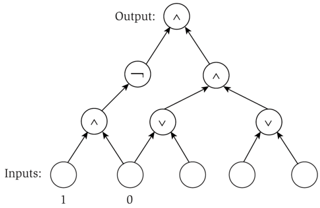

Figure 8.4 A circuit with three inputs, two additional sources that have assigned truth values, and one output.

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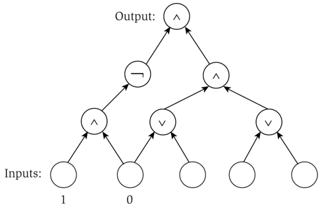

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CIRCUIT SATISFIABILITY

INSTANCE: A circuit K.

QUESTION: Is there a truth assignment to the inputs that causes the output to have value 1?

Skip proof; read textbook or Chapter 2.6 of Garey and Johnson.

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Proving Circuit Satisfiability is $\mathcal{NP}$-Complete

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- View $B(\cdot, \cdot)$ as an algorithm on $n + p(n)$ bits.
- Convert B to a polynomial-sized circuit K with $n + p(n)$ sources.
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- $s \in X$ iff there is an assignment of the input bits of K that makes K satisfiable.

Example of Transformation to Circuit Satisfiability

- Does a graph G on n nodes have a two-node independent set?

Example of Transformation to Circuit Satisfiability

- Does a graph G on n nodes have a two-node independent set?
- s encodes the graph G with $\binom{n}{2}$ bits.
- t encodes the independent set with n bits.
- Certifier needs to check if
  1. at least two bits in t are set to 1 and
  2. no two bits in t are set to 1 if they form the ends of an edge (the corresponding bit in s is set to 1).

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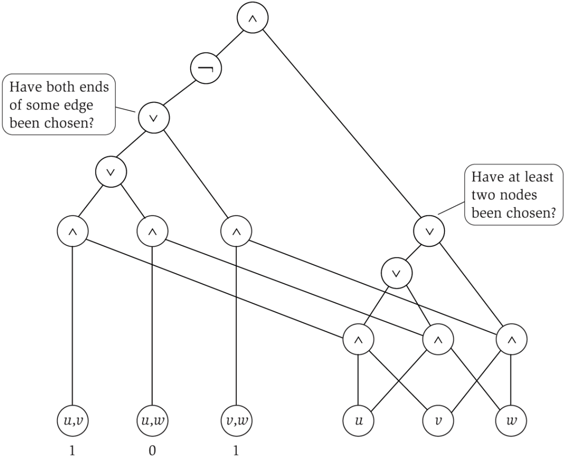

Figure 8.5 A circuit to verify whether a 3-node graph contains a 2-node independent set.

Asymmetry of Certification

- Definition of efficient certification and $\mathcal{NP}$ is fundamentally asymmetric:
  - An input s is a "yes" instance iff there exists a short certificate t such that $B(s, t) = \texttt{yes}$.
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  - An input s is a "no" instance iff *for all* short certificates t, $B(s, t) = \texttt{no}$. The definition of $\mathcal{NP}$ does not guarantee a short proof for "no" instances.

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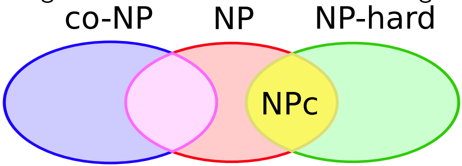

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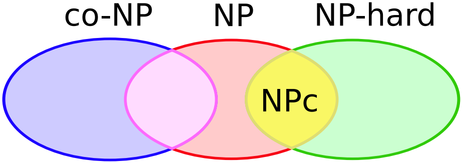

- Open problem: Is $\mathcal{NP} = $ co-$\mathcal{NP}$?
- Claim: If $\mathcal{NP} \neq$ co-$\mathcal{NP}$ then $\mathcal{P} \neq \mathcal{NP}$.

Good Characterisations: the Class $\mathcal{NP} \cap$ co-$\mathcal{NP}$

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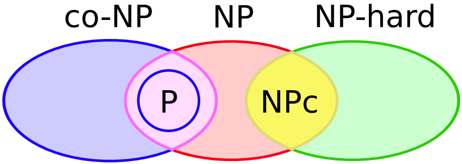

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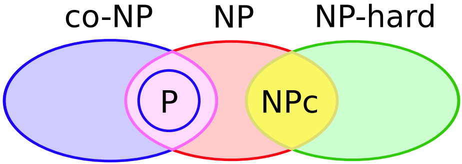

- Claim: $\mathcal{P} \subseteq \mathcal{NP} \cap$ co-$\mathcal{NP}$.
- Open problem: Is $\mathcal{P} = \mathcal{NP} \cap$ co-$\mathcal{NP}$?