More NP-Complete Problems

Lecture 23

April 17, 2018

Most slides are courtesy Prof. Chekuri

Recap

NP: languages/problems that have polynomial time certifiers/verifiers

A problem X is **NP-Complete** iff

- X is in **NP**
- X is **NP-Hard**.

X is **NP-Hard** if for every Y in **NP**, $Y \leq_P X$.

Theorem (Cook-Levin)

SAT *is* **NP-Complete**.

Recap contd

Theorem (Cook-Levin)

SAT *is* **NP-Complete**.

Establish **NP-Complete**ness via reductions:

1. **SAT** is **NP-Complete**.
2. **SAT** $\leq_P$ **3-SAT** and hence 3-SAT is **NP-Complete**.
3. **3-SAT** $\leq_P$ **Independent Set** (which is in **NP**) and hence **Independent Set** is **NP-Complete**.
4. **Clique** is **NP-Complete**
5. **Vertex Cover** is **NP-Complete**
6. **Set Cover** is **NP-Complete**
7. **Hamilton Cycle** and **Hamiltonian Path** are **NP-Complete**
8. **3-Color** is **NP-Complete**

Today

NP vs **co-NP**

Prove

- **Hamiltonian Cycle** is **NP-Complete**
- **3-Coloring** is **NP-Complete**
- **Subset Sum** is **NP-Complete**

All via reductions from **3-SAT**

NP vs **co-NP**

NP: Problems with polynomial time verifier for a “yes” instance.

NP vs co-NP

NP: Problems with polynomial time verifier for a “yes” instance.

SAT: Given a CNF formula ϕ, does there exists a satisfying assignment?
- Poly-time verification (proof) for “yes” instances.

NP vs co-NP

NP: Problems with polynomial time verifier for a “yes” instance.

SAT: Given a CNF formula ϕ, does there exists a satisfying assignment?
- Poly-time verification (proof) for “yes” instances.

Definition

Given a decision problem $\boldsymbol{X}$, its **complement** $\bar{\boldsymbol{X}}$ is the same problem with “yes” and “no” answeres reversed.

NP vs co-NP

NP: Problems with polynomial time verifier for a "yes" instance.

SAT: Given a CNF formula ϕ, does there exists a satisfying assignment?
- Poly-time verification (proof) for "yes" instances.

Definition

Given a decision problem $\boldsymbol{X}$, its **complement** $\bar{\boldsymbol{X}}$ is the same problem with "yes" and "no" answeres reversed.

complement-SAT: Is ϕ always false?

NP vs co-NP

NP: Problems with polynomial time verifier for a "yes" instance.

SAT: Given a CNF formula ϕ, does there exists a satisfying assignment?
- Poly-time verification (proof) for "yes" instances.

Definition

Given a decision problem X, its **complement** $\bar{X}$ is the same problem with "yes" and "no" answeres reversed.

complement-SAT: Is ϕ always false?
- Poly-time verification (proof) for "no" instances.

NP vs co-NP

NP: Problems with polynomial time verifier for a "yes" instance.

SAT: Given a CNF formula ϕ, does there exists a satisfying assignment?
- Poly-time verification (proof) for "yes" instances.

Definition

Given a decision problem X, its **complement** $\bar{X}$ is the same problem with "yes" and "no" answeres reversed.

complement-SAT: Is ϕ always false?
- Poly-time verification (proof) for "no" instances.

co-NP: Complements of decision problems in NP.

- **No-Hamiltonian-Cycle**, **Is-Prime**, **No-Subset-Sum**..

NP vs co-NP

NP: Problems with polynomial time verifier for a "yes" instance.

SAT: Given a CNF formula ϕ, does there exists a satisfying assignment?
- Poly-time verification (proof) for "yes" instances.

Definition

Given a decision problem X, its **complement** $\bar{X}$ is the same problem with "yes" and "no" answeres reversed.

complement-SAT: Is ϕ always false?
- Poly-time verification (proof) for "no" instances.

co-NP: Complements of decision problems in NP.

- **No-Hamiltonian-Cycle**, **Is-Prime**, **No-Subset-Sum**..
- Poly-time verification for "no" instances
- "no" instances can be solved in non-deterministic polynomial time.

Integer Factorization

Given integers q and n, is there a prime factor of q larger than n?

Input size: $\log(q) + \log(n)$

Integer Factorization

Given integers q and n, is there a prime factor of q larger than n?

Input size: $\log(q) + \log(n)$

Verifier for a "yes" instance?

Integer Factorization

Given integers q and n, is there a prime factor of q larger than n?

Input size: $\log(q) + \log(n)$

Verifier for a "yes" instance?

Verifier for a "no" instance?

Integer Factorization

Given integers q and n, is there a prime factor of q larger than n?

Input size: $\log(q) + \log(n)$

Verifier for a "yes" instance?

Verifier for a "no" instance?

Int-Factorization $\in$ **NP** $\cap$ **co-NP**.

Integer Factorization

Given integers q and n, is there a prime factor of q larger than n?

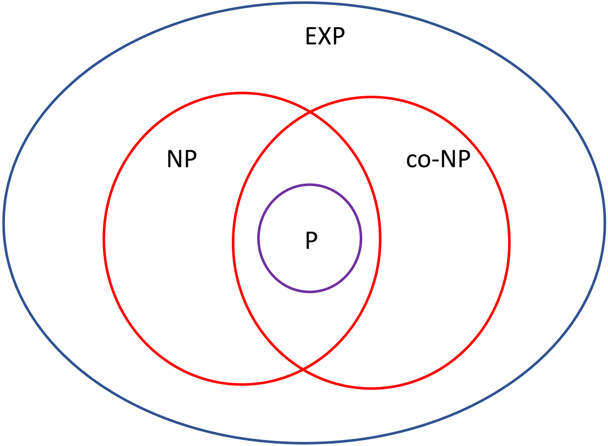
Input size: $\log(q) + \log(n)$

Verifier for a "yes" instance?

Verifier for a "no" instance?

Int-Factorization $\in$ **NP** $\cap$ **co-NP**. But not known to be in **P**.

Landscape of Containment



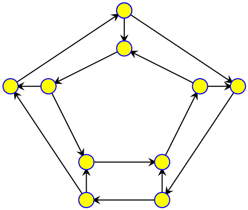
Part I

NP-Completeness of Hamiltonian Cycle

Directed Hamiltonian Cycle

Input Given a directed graph $G = (V, E)$ with n vertices

Goal Does G have a Hamiltonian cycle?

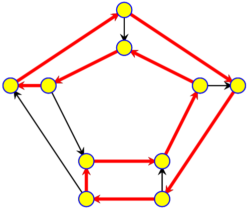


Directed Hamiltonian Cycle

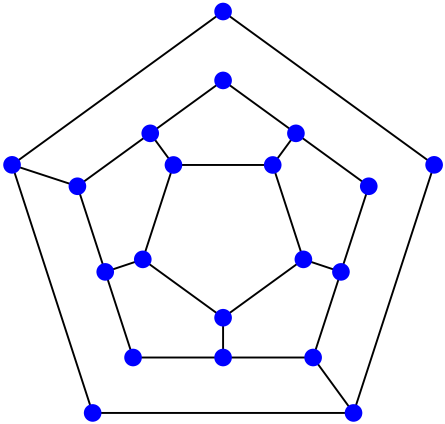
Input Given a directed graph $G = (V, E)$ with n vertices

Goal Does G have a Hamiltonian cycle?

- A Hamiltonian cycle is a cycle in the graph that visits every vertex in G exactly once



Is the following graph Hamiltonianan?



(A) Yes.

(B) No.

Directed Hamiltonian Cycle is **NP-Complete**

- Directed Hamiltonian Cycle is in ***NP***
  - Certificate: Sequence of vertices
  - Certifier: Check if every vertex (except the first) appears exactly once, and that consecutive vertices are connected by a directed edge
- Hardness: We will show
  3-SAT $\leq_P$ Directed Hamiltonian Cycle

Reduction

Given 3-SAT formula φ create a graph G_φ such that

- G_φ has a Hamiltonian cycle if and only if φ is satisfiable
- G_φ should be constructible from φ by a polynomial time algorithm $\mathcal{A}$

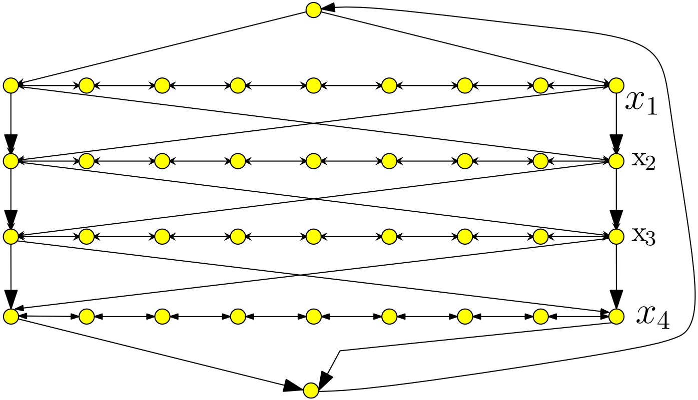
Notation: φ has n variables $x_1, x_2, \ldots, x_n$ and m clauses $C_1, C_2, \ldots, C_m$.

Reduction: First Ideas

- Viewing SAT: Assign values to n variables, and each clauses has 3 ways in which it can be satisfied.
- Construct graph with 2^n Hamiltonian cycles, where each cycle corresponds to some boolean assignment.
- Then add more graph structure to encode constraints on assignments imposed by the clauses.

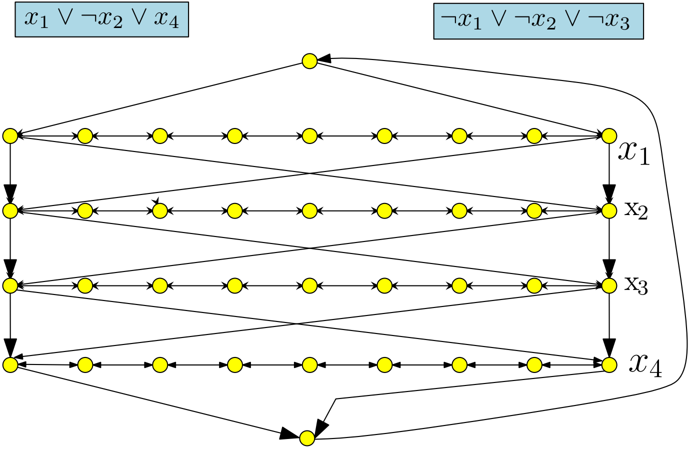
The Reduction: Phase I

- Traverse path $\boldsymbol{i}$ from left to right iff $\boldsymbol{x_i}$ is set to true
- Each path has $\mathbf{3(m+1)}$ nodes where $\boldsymbol{m}$ is number of clauses in φ; nodes numbered from left to right ($\mathbf{1}$ to $\mathbf{3m+3}$)



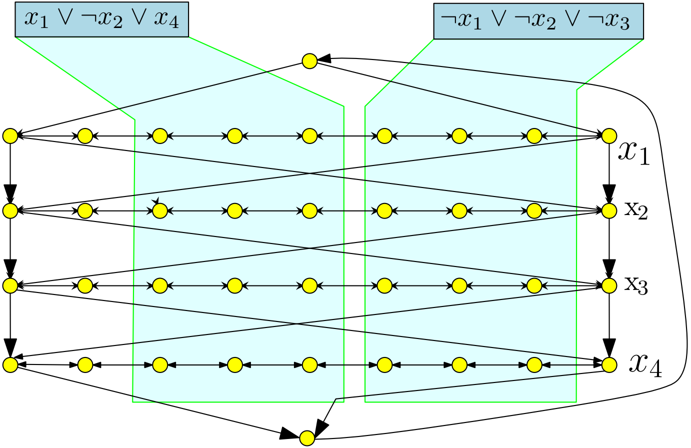
The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j+1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j+1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



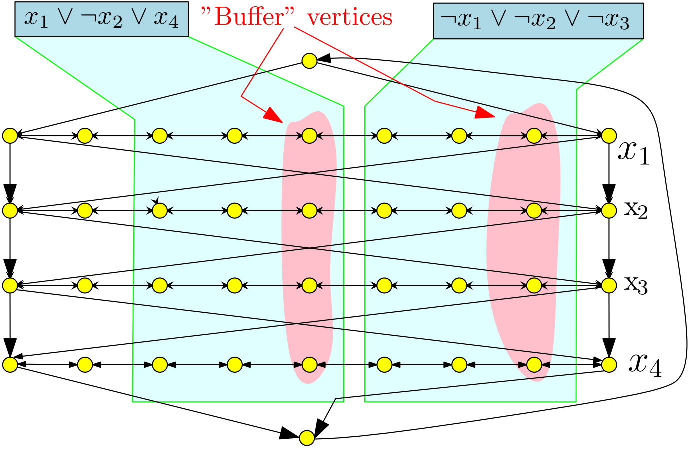
The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j + 1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j + 1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



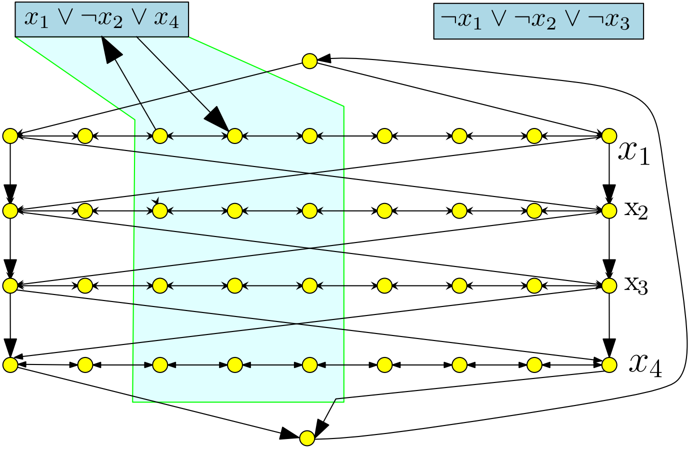
The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j + 1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j + 1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



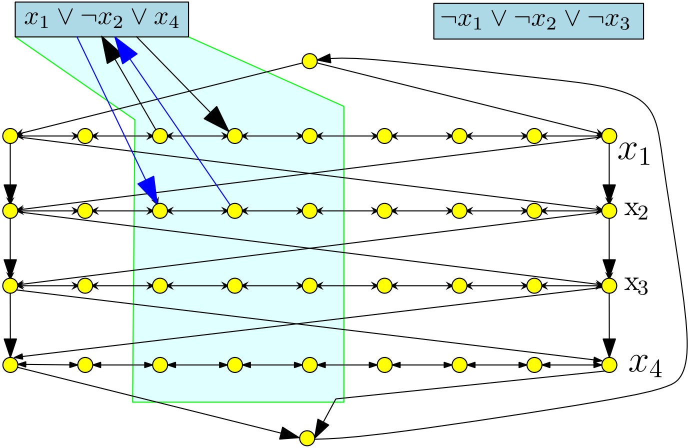
The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j + 1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j + 1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



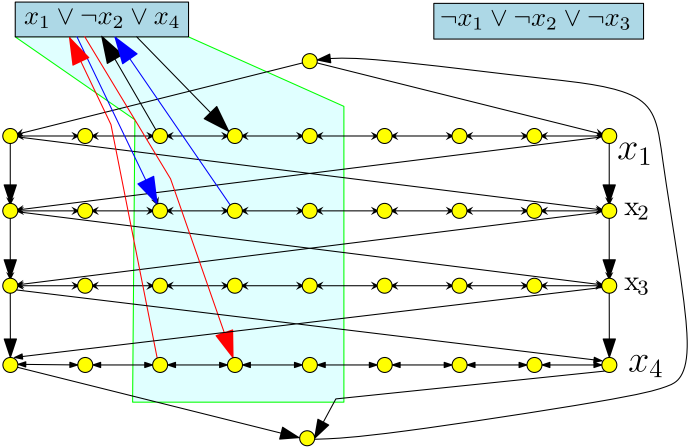
The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j + 1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j + 1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



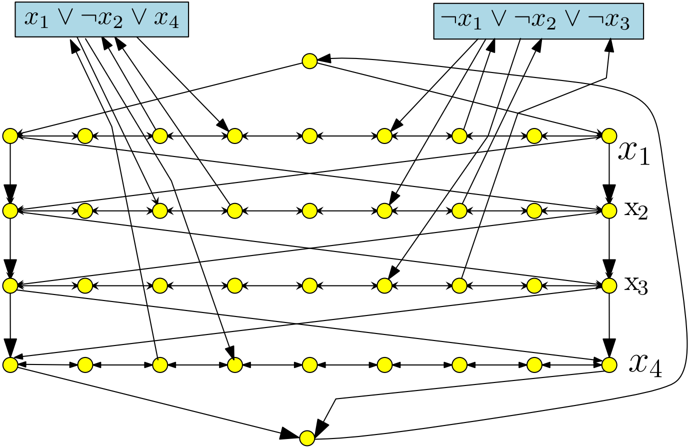
The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j+1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j+1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



The Reduction: Phase II

- Add vertex c_j for clause C_j. c_j has edge *from* vertex $3j$ and *to* vertex $3j+1$ on path i if x_i appears in clause C_j, and has edge *from* vertex $3j+1$ and *to* vertex $3j$ if $\neg x_i$ appears in C_j.



Correctness Proof

Proposition

φ has a satisfying assignment iff G_φ has a Hamiltonian cycle.

Proof.

$\Rightarrow$ Let a be the satisfying assignment for φ. Define Hamiltonian cycle as follows

- If $a(x_i) = 1$ then traverse path i from left to right
- If $a(x_i) = 0$ then traverse path i from right to left
- For each clause, path of at least one variable is in the "right" direction to splice in the node corresponding to clause □

Hamiltonian Cycle $\Rightarrow$ Satisfying assignment

Suppose Π is a Hamiltonian cycle in G_φ

- If Π enters c_j (vertex for clause C_j) from vertex $3j$ on path i then it must leave the clause vertex on edge to $3j+1$ on the *same path* i

Hamiltonian Cycle $\Rightarrow$ Satisfying assignment

Suppose Π is a Hamiltonian cycle in G_φ

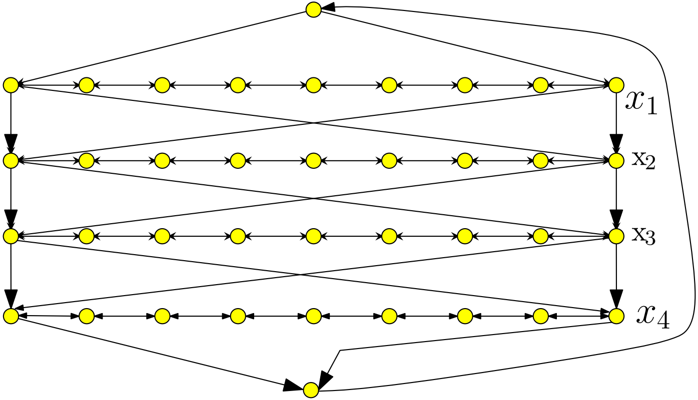
- If Π enters c_j (vertex for clause C_j) from vertex $3j$ on path i then it must leave the clause vertex on edge to $3j + 1$ on the *same path* i
  - If not, then only unvisited neighbor of $3j + 1$ on path i is $3j + 2$
  - Thus, we don't have two unvisited neighbors (one to enter from, and the other to leave) to have a Hamiltonian Cycle

Hamiltonian Cycle $\Rightarrow$ Satisfying assignment

Suppose Π is a Hamiltonian cycle in G_φ

- If Π enters c_j (vertex for clause C_j) from vertex $3j$ on path i then it must leave the clause vertex on edge to $3j + 1$ on the *same path* i
  - If not, then only unvisited neighbor of $3j + 1$ on path i is $3j + 2$
  - Thus, we don't have two unvisited neighbors (one to enter from, and the other to leave) to have a Hamiltonian Cycle
- Similarly, if Π enters c_j from vertex $3j + 1$ on path i then it must leave the clause vertex c_j on edge to $3j$ on path i

Example



Hamiltonian Cycle $\implies$ Satisfying assignment (contd)

- Thus, vertices visited immediately before and after C_i are connected by an edge
- We can remove c_j from cycle, and get Hamiltonian cycle in $G - c_j$
- Consider Hamiltonian cycle in $G - \{c_1, \ldots c_m\}$; it traverses each path in only one direction, which determines the truth assignment

Is covering by cycles hard?

Given a directed graph G, deciding if G can be covered by vertex disjoint cycles (each of length at least two) is

(A) **NP-Hard**.

(B) **NP-Complete**.

(C) **P**.

(D) IDK.

Hamiltonian Cycle

Problem

Input *Given* *undirected* *graph* $\boldsymbol{G = (V, E)}$

Goal *Does* $\boldsymbol{G}$ *have a Hamiltonian cycle? That is, is there a cycle that visits every vertex exactly one (except start and end vertex)?*

NP-Completeness

Theorem

Hamiltonian cycle *problem for* ***undirected*** *graphs is* ***NP-Complete****.*

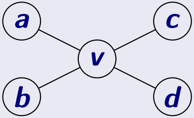
Proof.

- The problem is in **NP**; proof left as exercise.
- Hardness proved by reducing Directed Hamiltonian Cycle to this problem □

Reduction Sketch

Goal: Given directed graph G, need to construct undirected graph G' such that G has Hamiltonian cycle iff G' has Hamiltonian cycle

Reduction

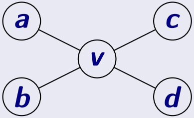


Reduction Sketch

Goal: Given directed graph G, need to construct undirected graph G' such that G has Hamiltonian cycle iff G' has Hamiltonian cycle

Reduction

- Replace each vertex v by 3 vertices: v_{in}, v, and v_{out}

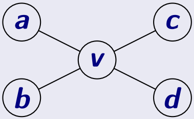


Reduction Sketch

Goal: Given directed graph G, need to construct undirected graph G' such that G has Hamiltonian cycle iff G' has Hamiltonian cycle

Reduction

- Replace each vertex v by 3 vertices: v_{in}, v, and v_{out}
- A directed edge (u, v) is replaced by edge (u_{out}, v_{in})

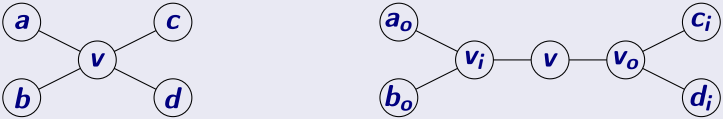


Reduction Sketch

Goal: Given directed graph G, need to construct undirected graph G' such that G has Hamiltonian cycle iff G' has Hamiltonian cycle

Reduction

- Replace each vertex v by 3 vertices: v_{in}, v, and v_{out}
- A directed edge (u, v) is replaced by edge (u_{out}, v_{in})



Reduction: Wrapup

- The reduction is polynomial time (exercise)
- The reduction is correct (exercise)

Hamiltonian Path

Input Given a directed graph $G = (V, E)$ with n vertices

Goal Does G have a Hamiltonian path?

- A Hamiltonian path is a path in the graph that visits every vertex in G exactly once

Hamiltonian Path

Input Given a directed graph $G = (V, E)$ with n vertices

Goal Does G have a Hamiltonian path?

- A Hamiltonian path is a path in the graph that visits every vertex in G exactly once

Exercise: Modify the reduction from **3-SAT** to **Hamilton cycle** to prove that **3-SAT** reduces to **Hamilton path**.

Hamiltonian Path

Input Given a directed graph $G = (V, E)$ with n vertices

Goal Does G have a Hamiltonian path?

- A Hamiltonian path is a path in the graph that visits every vertex in G exactly once

Exercise: Modify the reduction from **3-SAT** to **Hamilton cycle** to prove that **3-SAT** reduces to **Hamilton path**.

Exercise: Also prove that **Hamilton path** in undirected graphs is **NP-Complete**.

Part II

NP-Completeness of Graph Coloring

Graph Coloring

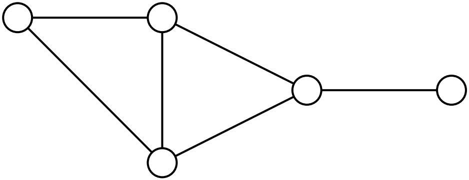
Problem: Graph Coloring

Instance: $G = (V, E)$: Undirected graph, integer k.
Question: Can the vertices of the graph be colored using k colors so that vertices connected by an edge do not get the same color?

Graph 3-Coloring

Problem: 3 Coloring

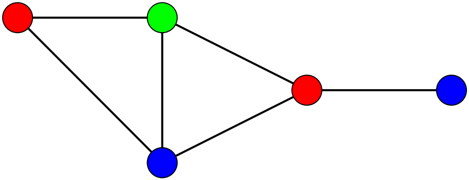
Instance: $G = (V, E)$: Undirected graph.
Question: Can the vertices of the graph be colored using $\mathbf{3}$ colors so that vertices connected by an edge do not get the same color?



Graph 3-Coloring

Problem: 3 Coloring

Instance: $G = (V, E)$: Undirected graph.
Question: Can the vertices of the graph be colored using **3** colors so that vertices connected by an edge do not get the same color?



Graph Coloring

Observation: If G is colored with k colors then each color class (nodes of same color) form an independent set in G. Thus, G can be partitioned into k independent sets iff G is k-colorable.

Graph Coloring

Observation: If G is colored with k colors then each color class (nodes of same color) form an independent set in G. Thus, G can be partitioned into k independent sets iff G is k-colorable.

Graph 2-Coloring can be decided in polynomial time.

Graph Coloring

Observation: If G is colored with k colors then each color class (nodes of same color) form an independent set in G. Thus, G can be partitioned into k independent sets iff G is k-colorable.

Graph 2-Coloring can be decided in polynomial time.

G is 2-colorable iff G is bipartite!

Graph Coloring

Observation: If G is colored with k colors then each color class (nodes of same color) form an independent set in G. Thus, G can be partitioned into k independent sets iff G is k-colorable.

Graph 2-Coloring can be decided in polynomial time.

G is 2-colorable iff G is bipartite! There is a linear time algorithm to check if G is bipartite using **BFS**.

Graph Coloring and Register Allocation

Register Allocation

Assign variables to (at most) k registers such that variables needed at the same time are not assigned to the same register

Interference Graph

Vertices are variables, and there is an edge between two vertices, if the two variables are "live" at the same time.

Graph Coloring and Register Allocation

Register Allocation

Assign variables to (at most) k registers such that variables needed at the same time are not assigned to the same register

Interference Graph

Vertices are variables, and there is an edge between two vertices, if the two variables are "live" at the same time.

Observations

- [Chaitin] Register allocation problem is equivalent to coloring the interference graph with k colors
- Moreover, **3-COLOR** $\leq_P$ **k-Register Allocation**, for any $k \geq 3$

Class Room Scheduling

Given n classes and their meeting times, are k rooms sufficient?

Class Room Scheduling

Given n classes and their meeting times, are k rooms sufficient?

Reduce to Graph k-Coloring problem

Create graph G

- a node v_i for each class i
- an edge between v_i and v_j if classes i and j *conflict*

Class Room Scheduling

Given n classes and their meeting times, are k rooms sufficient?

Reduce to Graph k-Coloring problem

Create graph G

- a node v_i for each class i
- an edge between v_i and v_j if classes i and j *conflict*

Exercise: G is k-colorable iff k rooms are sufficient

Frequency Assignments in Cellular Networks

Cellular telephone systems that use Frequency Division Multiple Access (FDMA) (example: GSM in Europe and Asia and AT&T in USA)

- Breakup a frequency range $[a, b]$ into disjoint *bands* of frequencies $[a_0, b_0], [a_1, b_1], \ldots, [a_k, b_k]$
- Each cell phone tower (simplifying) gets one band
- Constraint: nearby towers cannot be assigned same band, otherwise signals will interference

Frequency Assignments in Cellular Networks

Cellular telephone systems that use Frequency Division Multiple Access (FDMA) (example: GSM in Europe and Asia and AT&T in USA)

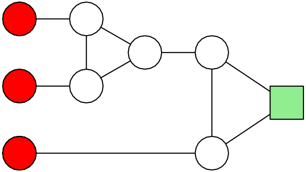
- Breakup a frequency range $[a, b]$ into disjoint *bands* of frequencies $[a_0, b_0], [a_1, b_1], \ldots, [a_k, b_k]$
- Each cell phone tower (simplifying) gets one band
- Constraint: nearby towers cannot be assigned same band, otherwise signals will interference

Problem: given k bands and some region with n towers, is there a way to assign the bands to avoid interference?

Can reduce to k-coloring by creating intereference/conflict graph on towers.

3 color this gadget.

You are given three colors: red, green and blue. Can the following graph be three colored in a valid way (assuming the four nodes are already colored as indicated).

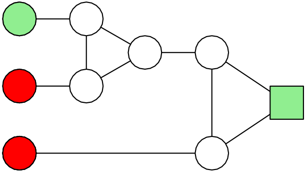


(A) Yes.

(B) No.

3 color this gadget II

You are given three colors: red, green and blue. Can the following graph be three colored in a valid way (assuming the four nodes are already colored as indicated).



(A) Yes.

(B) No.

3-Coloring is NP-Complete

- **3-Coloring** is in **NP**.
  - Certificate: for each node a color from $\{1, 2, 3\}$.
  - Certifier: Check if for each edge (u, v), the color of u is different from that of v.
- Hardness: We will show **3-SAT** $\leq_P$ **3-Coloring**.

Reduction Idea

Start with **3SAT** formula (i.e., $3\mathrm{CNF}$ formula) φ with n variables $x_1, \ldots, x_n$ and m clauses $C_1, \ldots, C_m$. Create graph G_φ such that G_φ is 3-colorable iff φ is satisfiable

- need to establish truth assignment for $x_1, \ldots, x_n$ via colors for some nodes in G_φ.

Reduction Idea

Start with **3SAT** formula (i.e., $3\mathrm{CNF}$ formula) φ with n variables $x_1, \ldots, x_n$ and m clauses $C_1, \ldots, C_m$. Create graph G_φ such that G_φ is 3-colorable iff φ is satisfiable

- need to establish truth assignment for $x_1, \ldots, x_n$ via colors for some nodes in G_φ.
- create triangle with node True, False, Base

Reduction Idea

Start with **3SAT** formula (i.e., $\mathbf{3}\mathrm{CNF}$ formula) φ with n variables $x_1, \ldots, x_n$ and m clauses $C_1, \ldots, C_m$. Create graph G_φ such that G_φ is 3-colorable iff φ is satisfiable

- need to establish truth assignment for $x_1, \ldots, x_n$ via colors for some nodes in G_φ.
- create triangle with node True, False, Base
- for each variable x_i two nodes v_i and $\bar{v}_i$ connected in a triangle with common Base

Reduction Idea

Start with **3SAT** formula (i.e., $3\mathrm{CNF}$ formula) φ with n variables $x_1, \ldots, x_n$ and m clauses $C_1, \ldots, C_m$. Create graph G_φ such that G_φ is 3-colorable iff φ is satisfiable

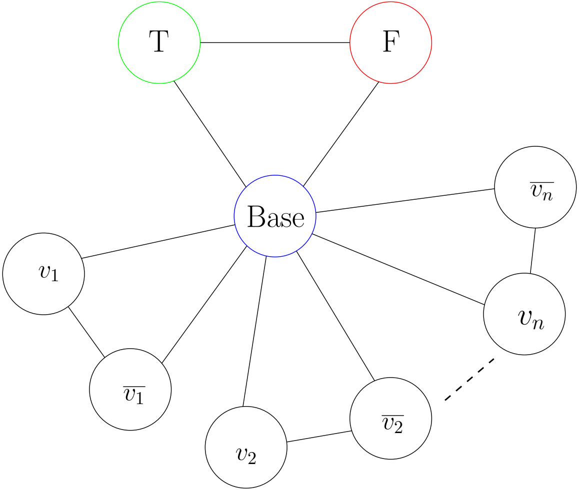
- need to establish truth assignment for $x_1, \ldots, x_n$ via colors for some nodes in G_φ.
- create triangle with node True, False, Base
- for each variable x_i two nodes v_i and $\bar{v}_i$ connected in a triangle with common Base
- If graph is 3-colored, either v_i or $\bar{v}_i$ gets the same color as True. Interpret this as a truth assignment to v_i

Reduction Idea

Start with **3SAT** formula (i.e., $3\mathrm{CNF}$ formula) φ with n variables $x_1, \ldots, x_n$ and m clauses $C_1, \ldots, C_m$. Create graph G_φ such that G_φ is 3-colorable iff φ is satisfiable

- need to establish truth assignment for $x_1, \ldots, x_n$ via colors for some nodes in G_φ.
- create triangle with node True, False, Base
- for each variable x_i two nodes v_i and $\bar{v}_i$ connected in a triangle with common Base
- If graph is 3-colored, either v_i or $\bar{v}_i$ gets the same color as True. Interpret this as a truth assignment to v_i
- Need to add constraints to ensure clauses are satisfied (next phase)

Figure

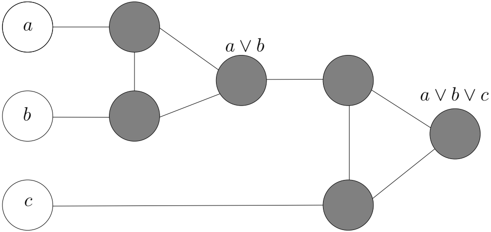


Clause Satisfiability Gadget

For each clause $C_j = (a \vee b \vee c)$, create a small gadget graph

- gadget graph connects to nodes corresponding to a, b, c
- needs to implement OR

OR-gadget-graph:

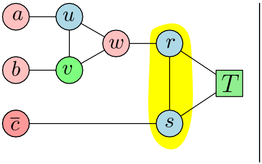


OR-Gadget Graph

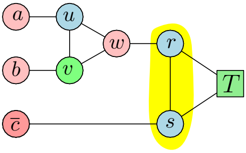
Property: if a, b, c are colored False in a 3-coloring then output node of OR-gadget has to be colored False.

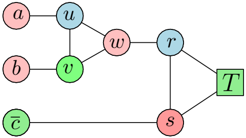
Property: if one of a, b, c is colored True then OR-gadget can be 3-colored such that output node of OR-gadget is colored True.

3 coloring of the clause gadget

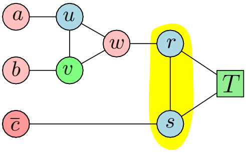


3 coloring of the clause gadget

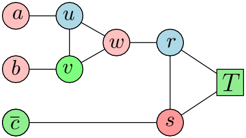




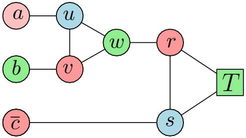
3 coloring of the clause gadget



FFF - **BAD**

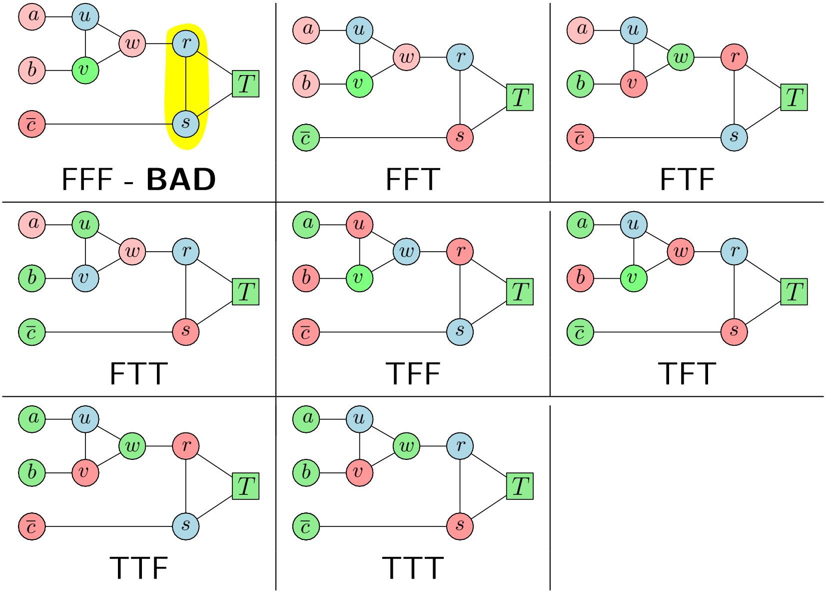


FFT



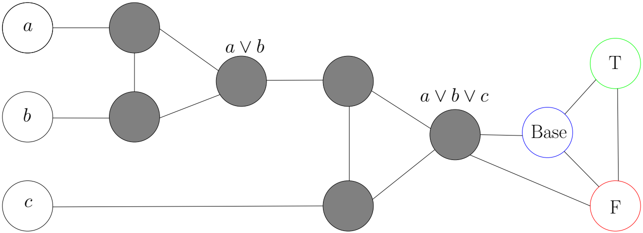
FTF

3 coloring of the clause gadget

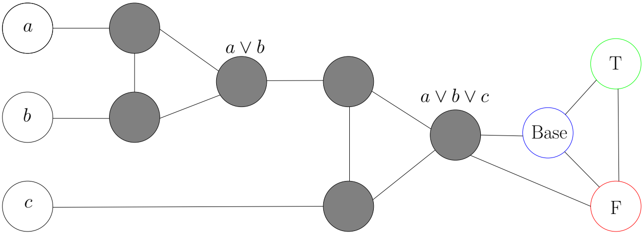


Reduction

- create triangle with nodes True, False, Base
- for each variable x_i two nodes v_i and $\bar{v}_i$ connected in a triangle with common Base
- for each clause $C_j = (a \vee b \vee c)$, add OR-gadget graph with input nodes a, b, c and connect output node of gadget to both False and Base



Reduction



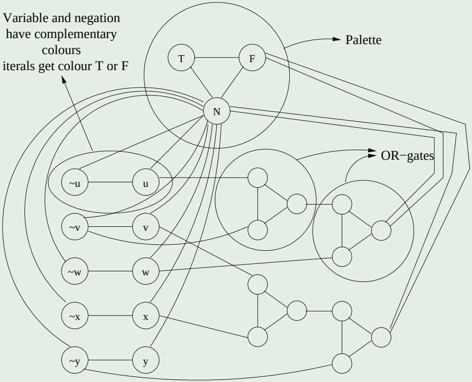
Claim

No legal $\mathbf{3}$*-coloring of above graph (with coloring of nodes* T, F, B *fixed) in which* $\mathbf{a}, \mathbf{b}, \mathbf{c}$ *are colored False. If any of* $\mathbf{a}, \mathbf{b}, \mathbf{c}$ *are colored True then there is a legal* $\mathbf{3}$*-coloring of above graph.*

Reduction Outline

Example

$\varphi = (u \lor \neg v \lor w) \land (v \lor x \lor \neg y)$



Correctness of Reduction

φ is satisfiable implies G_φ is 3-colorable

- if x_i is assigned True, color v_i True and $\bar{v}_i$ False

Correctness of Reduction

φ is satisfiable implies G_φ is 3-colorable

- if x_i is assigned True, color v_i True and $\bar{v}_i$ False
- for each clause $C_j = (a \vee b \vee c)$ at least one of a, b, c is colored True. OR-gadget for C_j can be 3-colored such that output is True.

Correctness of Reduction

φ is satisfiable implies G_φ is 3-colorable

- if x_i is assigned True, color v_i True and $\bar{v}_i$ False
- for each clause $C_j = (a \vee b \vee c)$ at least one of a, b, c is colored True. OR-gadget for C_j can be 3-colored such that output is True.

Correctness of Reduction

φ is satisfiable implies G_φ is 3-colorable

- if x_i is assigned True, color v_i True and $\bar{v}_i$ False
- for each clause $C_j = (a \vee b \vee c)$ at least one of a, b, c is colored True. OR-gadget for C_j can be 3-colored such that output is True.

G_φ is 3-colorable implies φ is satisfiable

- if v_i is colored True then set x_i to be True, this is a legal truth assignment

Correctness of Reduction

φ is satisfiable implies G_φ is 3-colorable

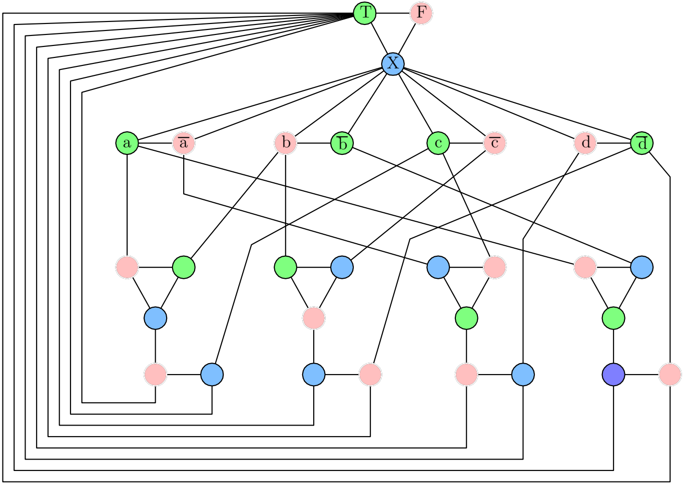
- if x_i is assigned True, color v_i True and $\bar{v}_i$ False
- for each clause $C_j = (a \vee b \vee c)$ at least one of a, b, c is colored True. OR-gadget for C_j can be 3-colored such that output is True.

G_φ is 3-colorable implies φ is satisfiable

- if v_i is colored True then set x_i to be True, this is a legal truth assignment
- consider any clause $C_j = (a \vee b \vee c)$. it cannot be that all a, b, c are False. If so, output of OR-gadget for C_j has to be colored False but output is connected to Base and False!

Graph generated in reduction...

... from 3SAT to 3COLOR



Part III

Hardness of **Subset Sum**

Subset Sum

Problem: Subset Sum

Instance: S - set of positive integers, t: - an integer number (Target)
Question: Is there a subset $X \subseteq S$ such that $\sum_{x \in X} x = t$?

Claim

Subset Sum *is* **NP-Complete**.

Vec Subset Sum

We will prove following problem is **NP-Complete**...

Problem: Vec Subset Sum

> **Instance:** S - set of n vectors of dimension k, each vector has non-negative numbers for its coordinates, and a target vector $\overrightarrow{t}$.
> **Question:** Is there a subset $X \subseteq S$ such that $\sum_{\overrightarrow{x} \in X} \overrightarrow{x} = \overrightarrow{t}$?

Reduction from **3SAT**.

Vec Subset Sum

Handling a single clause

Think about vectors as being lines in a table.

How to "select" exactly one of $x = 0$ and $x = 1$.

First gadget

Selecting between two lines.

Target	??	??	01	???
a_1	??	??	01	??
a_2	??	??	01	??

Vec Subset Sum

Handling a single clause

Think about vectors as being lines in a table.

How to "select" exactly one of $x = 0$ and $x = 1$.

First gadget

Selecting between two lines.

Target	??	??	01	???
a_1	??	??	01	??
a_2	??	??	01	??

Two rows for every variable x: selecting either $x = 0$ or $x = 1$.

Handling a clause...

We will have a column for every clause...

numbers	...	$C \equiv a \vee b \vee \overline{c}$	...
a	...	01	...
$\overline{a}$	...	00	...
b	...	01	...
$\overline{b}$	...	00	...
c	...	00	...
$\overline{c}$	...	01	...
C fix-up 1	000	07	000
C fix-up 2	000	08	000
C fix-up 3	000	09	000
TARGET		10	

3SAT to Vec Subset Sum

numbers	$a \vee \overline{a}$	$b \vee \overline{b}$	$c \vee \overline{c}$	$d \vee \overline{d}$	$D \equiv \overline{b} \vee c \vee \overline{d}$	$C \equiv a \vee b \vee \overline{c}$
a	1	0	0	0	00	01
$\overline{a}$	1	0	0	0	00	00
b	0	1	0	0	00	01
$\overline{b}$	0	1	0	0	01	00
c	0	0	1	0	01	00
$\overline{c}$	0	0	1	0	00	01
d	0	0	0	1	00	00
$\overline{d}$	0	0	0	1	01	01
C fix-up 1	0	0	0	0	00	07
C fix-up 2	0	0	0	0	00	08
C fix-up 3	0	0	0	0	00	09
D fix-up 1	0	0	0	0	07	00
D fix-up 2	0	0	0	0	08	00
D fix-up 3	0	0	0	0	09	00
TARGET	1	1	1	1	10	10

Vec Subset Sum to Subset Sum

numbers
010000000001
010000000000
000100000001
000100000100
000001000100
000001000001
000000010000
000000010101
000000000007
000000000008
000000000009
000000000700
000000000800
000000000900
010101011010

Other **NP-Complete** Problems

- **3-Dimensional Matching**
- **3-Partition**

Read book.

Subset Sum and Knapsack

Knapsack: Given n items with item i having non-negative integer size s_i and non-negative integer profit p_i, a knapsack of capacity B, and a target profit P, is there a subset S of items that can be packed in the knapsack and the profit of S is at least P?

Exercise: Show **Knapsack** is **NP-Complete** via reduction from **Subset Sum**

Subset Sum and Knapsack

Subset Sum can be solved in $O(nB)$ time using dynamic programming (exercise).

Subset Sum and Knapsack

Subset Sum can be solved in $O(nB)$ time using dynamic programming (exercise).

Implies that problem is hard only when numbers $a_1, a_2, \ldots, a_n$ are exponentially large compared to n. That is, each a_i requires polynomial in n bits.

Number problems of the above type are said to be **weakly NP-Complete**.

Number problems which are **NP-Complete** even when the numbers are written in unary are **strongly NP-Complete**.

A Strongly NP-Complete Number Problem

3-Partition: Given $3n$ numbers $a_1, a_2, \ldots, a_{3n}$ and target B can the numbers be partitioned into n groups of 3 each such that the sum of numbers in each group is exactly B?

Can further assume that each number a_i is between $B/3$ and $2B/3$.

Can reduce **3-D-Matching** to **3-Partition** in polynomial time such that each number a_i can be written in unary.

Need to Know **NP-Complete** Problems

- **SAT** and **3-SAT**
- **Independent Set**
- **Vertex Cover**
- **Clique**
- **Set Cover**
- **Hamiltonian Cycle** in Directed/Undirected Graphs
- **3-Coloring**
- **3-D Matching**
- **Subset Sum** and **Knapsack**