

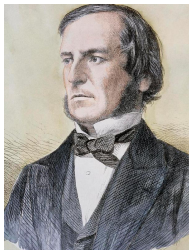
Subset Sum, and the
secret language of numbers

Boolean logic $x, y \in \{\text{TRUE}, \text{FALSE}\} = \{1, 0\}$

"x and y" $x \wedge y$

"x or y" $x \vee y$

"not x" $\bar{x}$ (or $\neg x$)



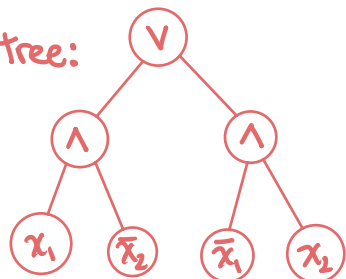
George Boole,
1815-1864

XOR ("exclusive-or")

(TRUE iff $x_1 \neq x_2$)

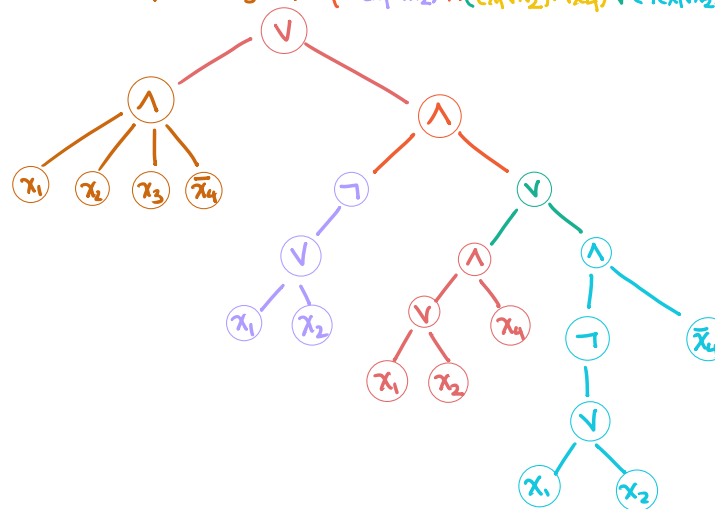
$$f(x_1, x_2) = (x_1 \wedge \bar{x}_2) \vee (\bar{x}_1 \wedge x_2)$$

as a tree:



Adding two bits $f(x_1, x_2, x_3, x_4) = \begin{cases} 1 & \text{if } x_1 + x_2 = x_3 x_4 \\ 0 & \text{otherwise} \end{cases}$

$$f(x_1, x_2, x_3, x_4) = (x_1 \wedge x_2 \wedge x_3 \wedge \bar{x}_4) \vee (\neg(x_1 \wedge x_2) \wedge ((x_1 \vee x_2) \wedge x_4) \vee (\neg(x_1 \vee x_2) \wedge \bar{x}_4))$$



Boolean Satisfiability

Input: Boolean formula $\varphi(x_1, x_2, \dots, x_n)$

• n variables • "size" m

e.g. $\varphi(\overset{\text{(false)}}{0}, \overset{\text{(true)}}{1}, \overset{\text{(false)}}{0}, \overset{\text{(true)}}{1}, \neg, \overset{\text{(false)}}{0}, \overset{\text{(true)}}{1}, \overset{\text{(false)}}{1}) = 0$

Goal: decide if φ is "satisfiable";

i.e., if there exists $x_1, x_2, \dots, x_n \in \{0, 1\}$
s.t. $\varphi(x_1, x_2, \dots, x_n) = 1$

"SAT Programming Language"

"x and y" $x \wedge y$

"x or y" $x \vee y$

"not x" $\bar{x}$ (or $\neg x$)

★ "z = x"

"both true or both false"
 $(z \wedge x) \vee (\bar{z} \wedge \bar{x})$

★ "if x then y
else z"

"(x=1, y=1) or (x=0, z=1)"
 $(x \wedge y) \vee (\bar{x} \wedge z)$

So Boolean algebra is very expressive

"search problem": we can recognize an answer (e.g. satisfying assignment x) when we see it (by evaluating $f(x)$).

- at the very least: we can try all x .
- harder "search problem" than "over/under"

Boolean Satisfiability

Input: Boolean formula $\varphi(x_1, x_2, \dots, x_n)$

- n variables
- "size" m

e.g. $\varphi(\overset{\text{(false)}}{0}, \overset{\text{(true)}}{1}, 0, 0, \neg, \overset{\text{(false)}}{1}, 1) = 0$

Boolean logic $x, y \in \{\text{TRUE}, \text{FALSE}\} = \{1, 0\}$

"x and y" $x \wedge y$

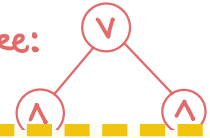
"x or y" $x \vee y$

"not x" $\bar{x}$ (or $\neg x$)

XOR ("exclusive-or") (TRUE iff $x_1 \neq x_2$)

$$f(x_1, x_2) = (x_1 \wedge \bar{x}_2) \vee (\bar{x}_1 \wedge x_2)$$

as a tree:



Goal

The Big Question

Is there a polynomial time algorithm for Boolean satisfiability?

x_2

$x_2 = x_3 x_4$

wise

$x_3 \wedge \bar{x}_4$

x_2

$x_2 \wedge x_4$

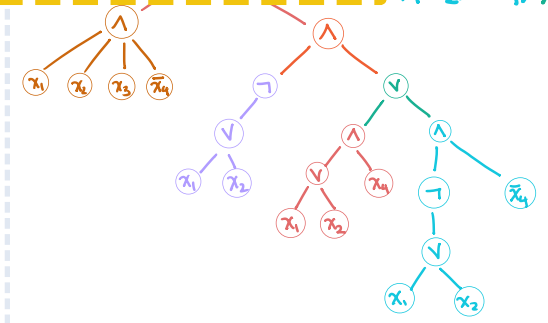
$(x_1 \vee x_2) \wedge \bar{x}_4$

"See"

answer (e.g. satisfying assignment x) when we see it (by evaluating $f(x)$).

- at the very least: we can try all x .

- harder "search problem" than "over/under"



"SAT Programming Language"

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★ "if x then y else z"

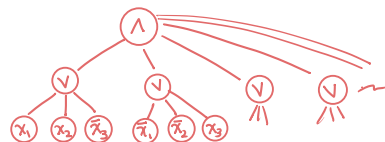
$$(x \wedge y) \vee (\bar{x} \wedge z)$$

CNF (Conjunctive Normal Form)

"and-of-or's"

$$f(x_1, \dots, x_n) =$$

$$(\bar{x}_1 \vee x_2 \vee \bar{x}_3) \wedge (\bar{x}_1 \vee \bar{x}_2 \vee x_3) \wedge (x_1 \vee x_2) \wedge \dots$$



(CNF-) SAT problem

Given boolean formula f in CNF, decide if f is satisfiable

More modest Question

Is there a polynomial time algorithm for CNF-satisfiability?

"CNF-SAT Programming Language"

"x and y"

$$x \wedge y$$

"x or y"

$$x \vee y$$

"not x"

$$\bar{x} \quad (\text{or } \neg x)$$

★ "z = x"

$$(z \wedge x) \vee (\bar{z} \wedge \bar{x})$$

$$= (z \vee (\bar{z} \wedge \bar{x})) \wedge (x \vee (\bar{z} \wedge \bar{x}))$$

$$= (z \vee \bar{z}) \wedge (z \vee \bar{x}) \wedge (x \vee \bar{z}) \wedge (x \vee \bar{x})$$

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★ "if x then y else z"

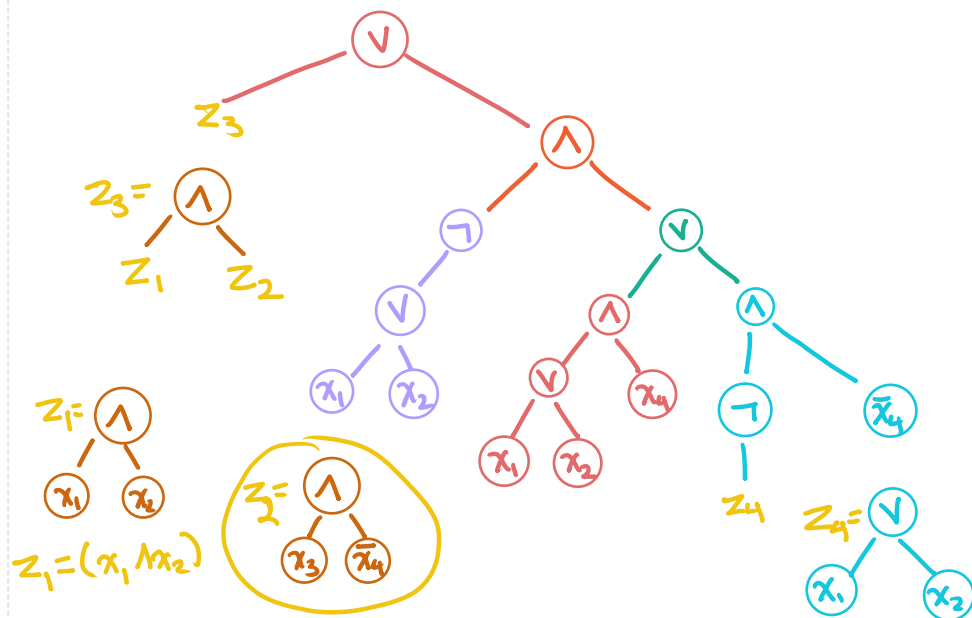
$$(x \wedge y) \vee (\bar{x} \wedge z)$$

$$= (x \vee \bar{x}) \wedge (y \vee \bar{x}) \wedge (x \vee z) \wedge (x \vee \bar{z})$$

$$= (y \vee \bar{x}) \wedge (x \vee z) \wedge (x \vee \bar{z})$$

So CNF is also very expressive

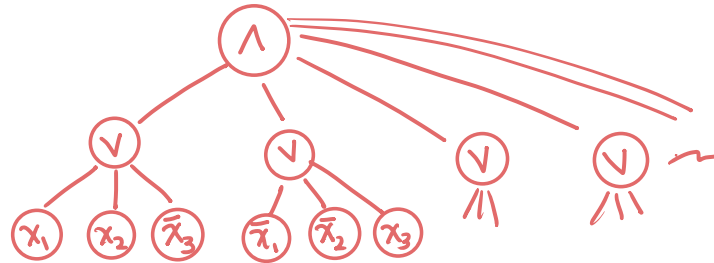
Theorem: there is a poly-time algo for Boolean SAT iff there is a poly-time algo for CNF-SAT.



more special case:

3-SAT

like CNF-SAT, except w/ exactly 3 variables per clause.



$$f(x_1, \dots, x_n) =$$

$$(\bar{x}_1 \vee x_2 \vee \bar{x}_3) \wedge (\bar{x}_1 \vee \bar{x}_2 \vee x_3) \wedge (\sim \vee \sim \vee \sim) \wedge \sim$$

"clause"

Is there a polytime algo for 3SAT?

Theorem: there is a poly-time algo for Boolean SAT iff there is a poly-time algo for 3-SAT.

Boolean logic $x, y \in \{\text{TRUE}, \text{FALSE}\} = \{1, 0\}$

"x and y" $x \wedge y$

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CNF (Conjunctive Normal Form)

"and-of-or's"



$$f(x_1, \dots, x_n) =$$

$$(\bar{x}_1 \vee x_2 \vee \bar{x}_3) \wedge (\bar{x}_1 \vee \bar{x}_2 \vee x_3) \wedge (\sim \vee \sim \vee \sim) \wedge \sim$$

"clause"

(CNF $\rightarrow$) SAT problem

Given boolean formula f in CNF, decide if f is satisfiable

"CNF-SAT Programming Language"

★ "z = x"

"both true or both false"

$$(z \wedge x) \vee (\bar{z} \wedge \bar{x})$$

$$= (z \vee \bar{x}) \wedge (x \vee \bar{z})$$

★ "if x then y else z"

"(x=1, y=1) or (x=0, y=0)"

$$(x \wedge y) \vee (\bar{x} \wedge \bar{y})$$

$$= (y \vee \bar{x}) \wedge (x \vee \bar{y})$$

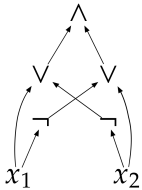
Theorem: there is a poly-time algo for Boolean SAT iff there is a poly-time algo for CNF-SAT.

Lemma. There is a polytime algo that, given a boolean formula $f(x_1, \dots, x_n)$ of size m , computes a CNF $g(x_1, \dots, x_p)$, w/ $p = O(m \log n)$ variables and size $O(m)$, s.t.

$$f \text{ is satisfiable} \Leftrightarrow g \text{ is satisfiable}$$

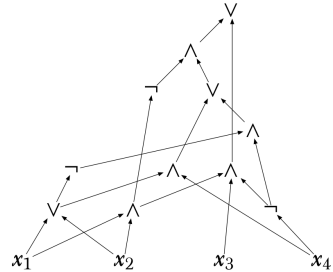
e.g. circuits

XOR ("exclusive-or")
(TRUE iff $x_1 \neq x_2$)

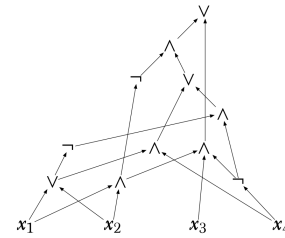
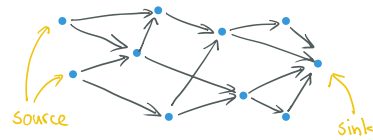


$$f(x_1, x_2) = (x_1 \wedge \bar{x}_2) \vee (\bar{x}_1 \wedge x_2)$$

Addition



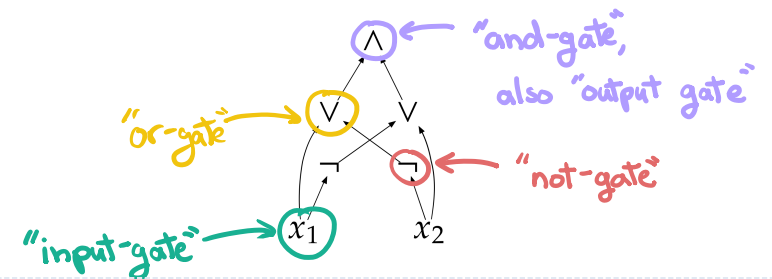
$$f(x_1, x_2, x_3, x_4) = \begin{cases} 1 & \text{if } x_1 + x_2 = x_3 x_4 \\ 0 & \text{otherwise} \end{cases}$$



(definition)

logical gates arranged as vertices
in a directed acyclic graph

"gates": take some inputs bits, output 1 bit



Circuit SAT

given a circuit, decide if it
is satisfiable

Theorem: there is a poly-time algo for
Boolean SAT iff there is a poly-time algo
for Circuit SAT

Conclusion

We want, but don't have, polynomial time algos for

Boolean SAT, CNF SAT, 3-SAT, or Circuit SAT

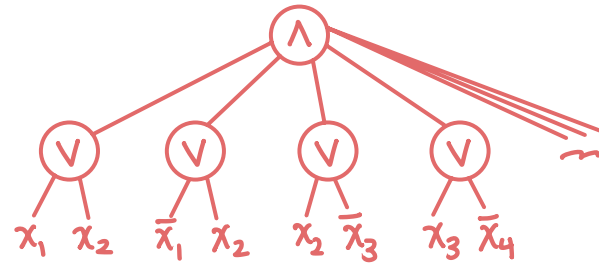
But we do know they are equivalent up to polynomial time!

2-SAT

like CNF-SAT, except w/ exactly 2 variables per clause.

$$f(x_1, \dots, x_n) =$$

$$(x_1 \vee x_2) \wedge (\bar{x}_1 \vee x_2) \wedge \underbrace{(x_2 \vee \bar{x}_3)}_{\text{clause}} \wedge (x_3 \vee \bar{x}_4) \wedge \dots$$



Max 2-SAT

like 2-SAT, except goal is to satisfy
maximum number of clauses.
(not necessarily all)

Is there a polytime algo for Max 2-SAT?

Boolean logic $x, y \in \{\text{TRUE}, \text{FALSE}\} = \{1, 0\}$

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"x or y" $x \vee y$

"not x" $\bar{x}$ (or $\neg x$)

CNF (Conjunctive Normal Form)

"and-of-or's"



$$f(x_1, \dots, x_n) =$$

$$(\bar{x}_1 \vee x_2 \vee \bar{x}_3) \wedge (\bar{x}_1 \vee \bar{x}_2 \vee x_3) \wedge (\dots)$$

(CNF $\rightarrow$) SAT problem

Given boolean formula f in CNF,
decide if f is satisfiable

"CNF-SAT Programming Language"

★ "z = x"

"both true or both false"

$$(z \wedge x) \vee (\bar{z} \wedge \bar{x})$$

$$= (z \vee \bar{x}) \wedge (x \vee \bar{z})$$

★ "if x then y
else z"

"(x=1, y=1) or (x=0, y=0)"

$$(x \wedge y) \vee (\bar{x} \wedge \bar{y})$$

$$= (y \vee \bar{x}) \wedge (x \vee \bar{y})$$

Theorem: there is a poly-time algo for
Boolean SAT iff there is a poly-time algo
for CNF-SAT.

Lemma. There is a polytime algo that,
given a boolean formula $f(x_1, \dots, x_p)$ of
size m , computes a CNF $g(x_1, \dots, x_p)$, w/
 $p = O(m \log n)$ variables and size $O(m)$, s.t.

f is satisfiable $\Leftrightarrow g$ is satisfiable

Theorem: there is a poly-time algo for
Boolean SAT iff there is a poly-time algo
for 3-SAT.

	Polytime Algo	Hard as ^(CNF-) SAT	Abstain
2SAT	57%	43% - 4	1
Max 2-SAT	22%	76%	
	17%	83% - 2	

let C be a sink SCC.

Complement $\bar{C}$ is a source SCC (why?)



Assign (all literals in) $C = \text{true}$, $\bar{C} = \text{false}$

Remove C and $\bar{C}$ and recurse on remaining SCC's

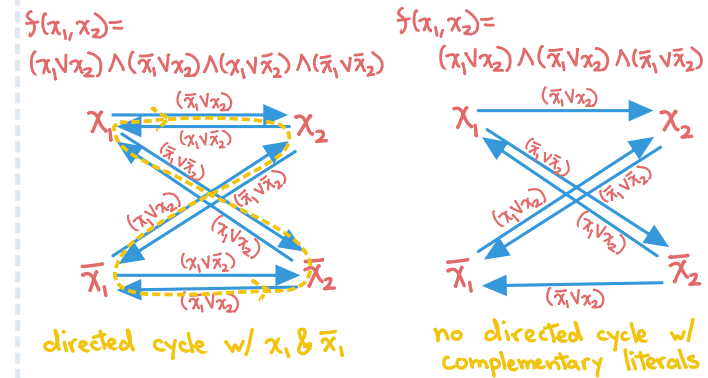
Key idea: assigning sinks to be true,
sources to be false
does not violate any edges

Implication graph

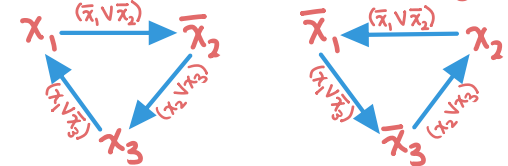
- vertex for each $x_i, \bar{x}_i$
- for clause $(a \vee b)$,

$$\bar{a} \xrightarrow{(a \vee b)} b \quad \bar{b} \xrightarrow{(a \vee b)} a$$

" $\bar{a} = \text{TRUE} \Rightarrow b = \text{TRUE}$ " " $\bar{b} = \text{TRUE} \Rightarrow a = \text{TRUE}$ "



all literals in SCC have same assignment



each SCC C has complement SCC $\bar{C}$
w/ negated literals & reversed edges

Fix a clause $(a \vee b \vee c)$

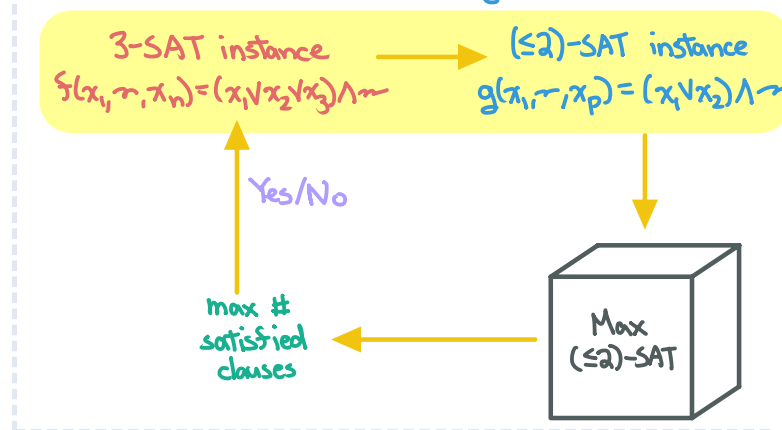
introduce new variable y

consider the 10 clauses

$(a), (b), (c), (\bar{a} \vee \bar{b}), (\bar{b} \vee \bar{c}), (\bar{c} \vee \bar{a}),$

$(y), (a \vee \bar{y}), (b \vee \bar{y}), (c \vee \bar{y})$

Theorem: A polytime algorithm for max (≤ 2) -SAT implies a polynomial time algorithm for SAT.



$(a, b, c) =$	(f, f, f)	(t, f, f)	(t, t, f)	(t, t, t)
$(a), (b), (c)$	0	1	2	3
$(\bar{a} \vee \bar{b}), (\bar{b} \vee \bar{c}), (\bar{c} \vee \bar{a})$	3	3	2	0
$\max_{y \in \{t, f\}} (y), (a \vee \bar{y}), (b \vee \bar{y}), (c \vee \bar{y})$	3	3	3	4
total	6	7	7	7

Theorem: A polytime algorithm for max 2-SAT implies a polynomial time algorithm for SAT.

(a, b, c) =	(f, f, f)	(t, f, f)	(t, t, f)	(t, t, t)
(a), (b), (c)	0	1	2	3
$(\bar{a} \vee \bar{b}), (\bar{b} \vee \bar{c}), (\bar{c} \vee \bar{a})$	3	3	2	0
$\max_{y \in \{t, f\}} (y), (a \vee y), (b \vee y), (c \vee y)$	3	3	3	4
total	6	7	7	7

3-SAT instance

$$f(x_1, \neg, x_n) = (x_1 \vee x_2 \vee x_3) \wedge \dots$$

(≤ 2)-SAT instance

$$g(x_1, \neg, x_p) = (x_1 \vee x_2) \wedge \dots$$

Yes/No

max #
satisfied
clauses

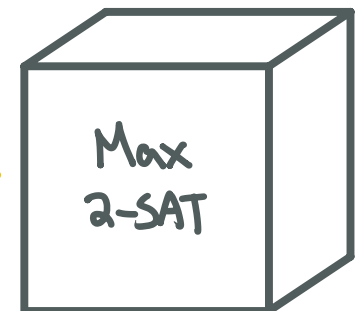


$$(a_i \vee \neg y_i) \wedge (a_i \vee \neg \bar{y}_i)$$

2-SAT instance
 $g(x_1, \neg, x_p) = (x_1 \vee x_2) \wedge \dots$

-k

max #
satisfied
clauses in g



e.g. Making change (\$)

93 cents = quarters,

..... dimes,

..... nickels,

..... pennies

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$, $T \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10

$T=52$

Another "search" problem

	Polytime Algo	Hard as ^(CNF-) SAT	Abstain
Subset Sum			

Subset Sum

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Ideas for algorithms?

Recursive Spec

(Subset-Sum)

$SS((x_1, \dots, x_n), T) =$

TRUE if there is a subset of $x_1, \dots, x_n$ summing to T ,
and FALSE otherwise

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
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e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$

Implementation

$SS((x_1, \dots, x_n), T)$

1. If $T < 0$ then return FALSE

2. If $T = 0$ then return TRUE

3. If $n = 0$ then return FALSE

4. Return $SS((x_2, \dots, x_n), T) \vee SS((x_2, \dots, x_n), T - x_1)$

Running time: $T(n) = T(n-1) + O(1) = O(2^n)$

Recursive Spec

(Subset-Sum)

$SS(i, S) = \text{TRUE}$ if there is a subset of $x_1, \dots, x_n$ summing to S , and FALSE otherwise

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$

Implementation

$SS(i, S)$

1. If $S < 0$ then return FALSE
2. If $S = 0$ then return TRUE
3. If $i > n$ then return FALSE
4. Return $SS(i+1, S) \vee SS(i+1, S - x_i)$

Running time:

$O(nT)$ subproblems

$O(1)$ time per subproblem

$O(nT)$ time overall

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}, T \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10

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	Polytime Algo	Hard as ^(CNF-) SAT	Abstain
Subset Sum			

Running time:

$O(nT)$ subproblems

$O(1)$ time per subproblem

$O(nT)$ time overall

"T" takes $\log(T)$ bits to write down

what if $T \approx 2^n$?

Sh*t. Any other ideas?

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
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Recursive Spec

(Subset-Sum)
 $SS(i, S) = \text{TRUE}$ if there is a subset of $x_1, \dots, x_n$ summing to S , FALSE otherwise

Implementation

$SS(i, S)$

1. If $S < 0$ then return FALSE
2. If $S = 0$ then return TRUE
3. If $n = 0$ then return FALSE
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Running time:

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$O(1)$ time per subproblem

$O(nT)$ time overall

Can we instead show that
Subset-Sum is hard as SAT?

Unlike previous problems, SubsetSum
looks nothing like SAT ~

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
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e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
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Recursive Spec

(Subset-Sum)
 $SS(i, S) = \text{TRUE}$ if there is a subset
of $x_1, \dots, x_n$ summing to S , FALSE otherwise

Implementation

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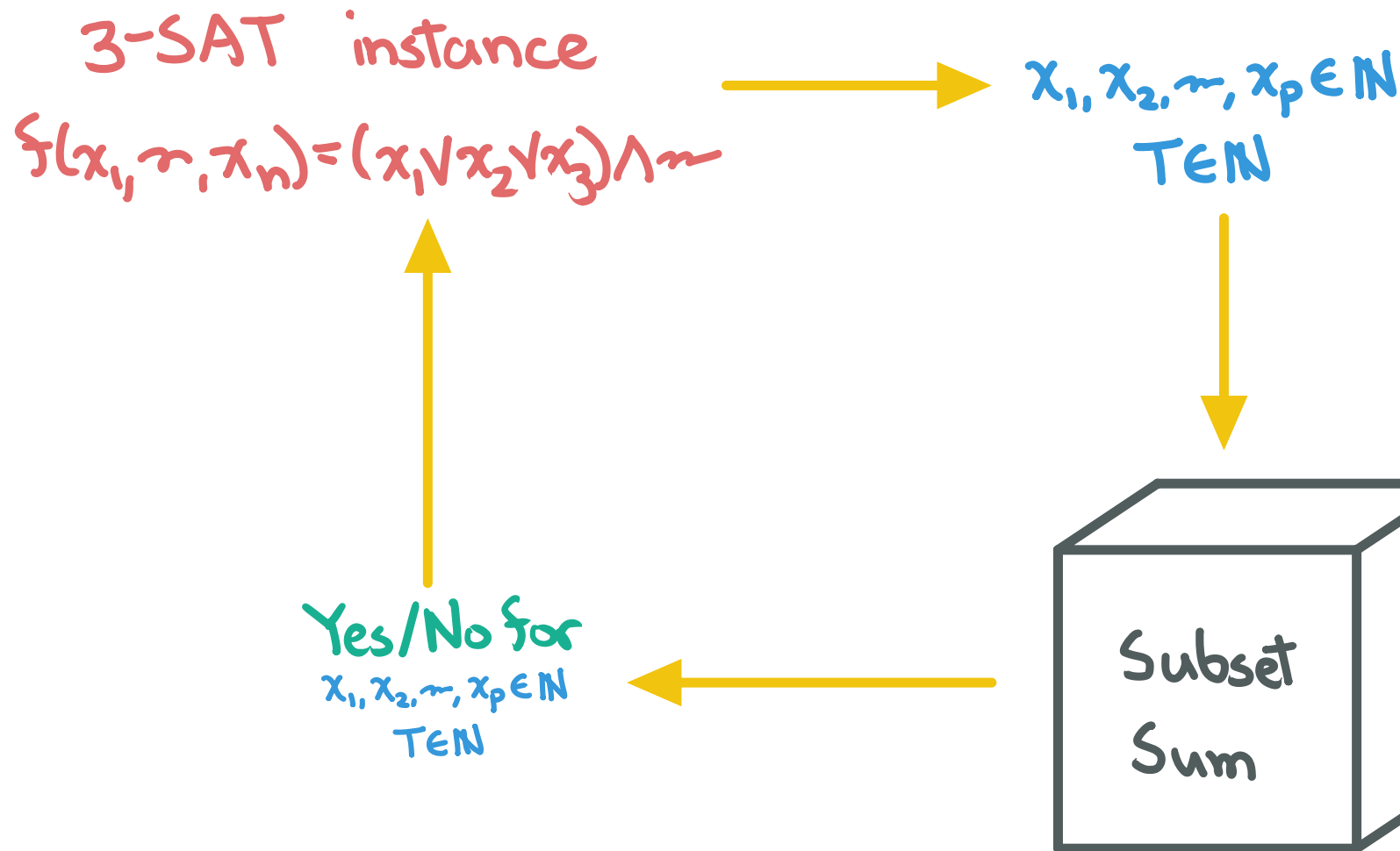
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Theorem: A polytime algo for subset-sum
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e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$

Proof setup.



Key idea: numbers are bit-strings too!

- use many digits
- each digit encodes 1 constraint

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• use many digits • each digit encodes 1 constraint

1. Recast 3SAT as "subset" problem

$X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

clause $(x_1 \vee \bar{x}_2 \vee x_3) = \text{set } \{x_1, \bar{x}_2, x_3\} \subset X$

Goal: find $S \subset X$ s.t.

Ⓐ for each clause C_i , $C_i \cap S = \emptyset$

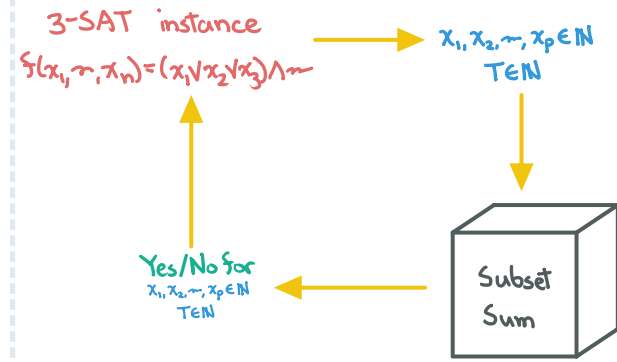
Ⓑ for each x_j , S contains (exactly) 1 of $\{x_j, \bar{x}_j\}$

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
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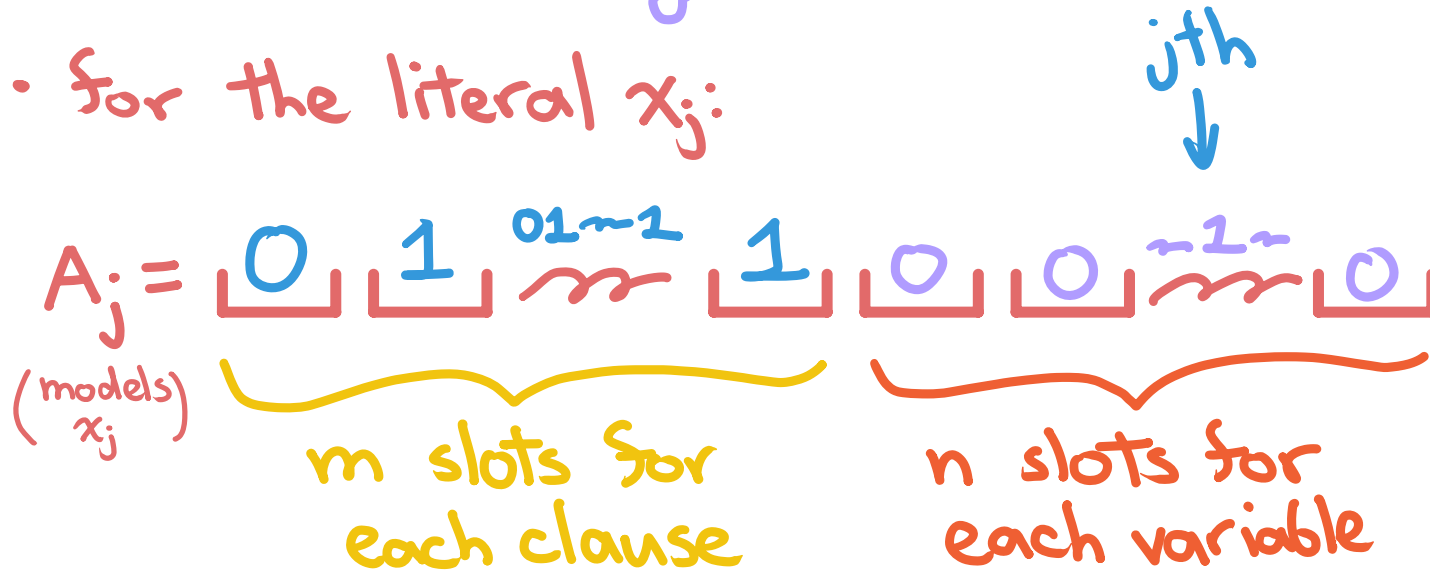
Key idea: numbers are bit-strings too!

- use many digits • each digit encodes 1 constraint

2. Start making #'s:

- we use mtn digits base 4

- for the literal x_j :



- for each clause C_i , set C_i th digit to $\begin{cases} 1 & \text{if } x_j \in C_i \\ 0 & \text{otherwise} \end{cases}$

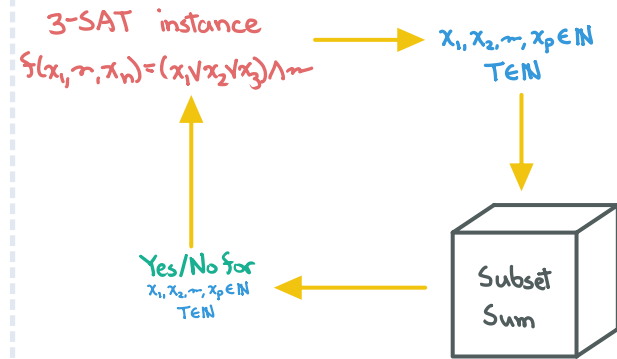
- set " x_j th digit" to 1, else 0

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$



1. Recast 3SAT as "subset" problem

$X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

clause $(x_1 \vee \bar{x}_2 \vee x_3) = \text{set } \{x_1, \bar{x}_2, x_3\} \subset X$

Goal: Find $S \subset X$ s.t.

(a) for each clause C_i , $C_i \cap S = \emptyset$

(b) for each x_j , S contains ^(exactly) 1 of $\{x_j, \bar{x}_j\}$

(not $\bar{x}_j$)

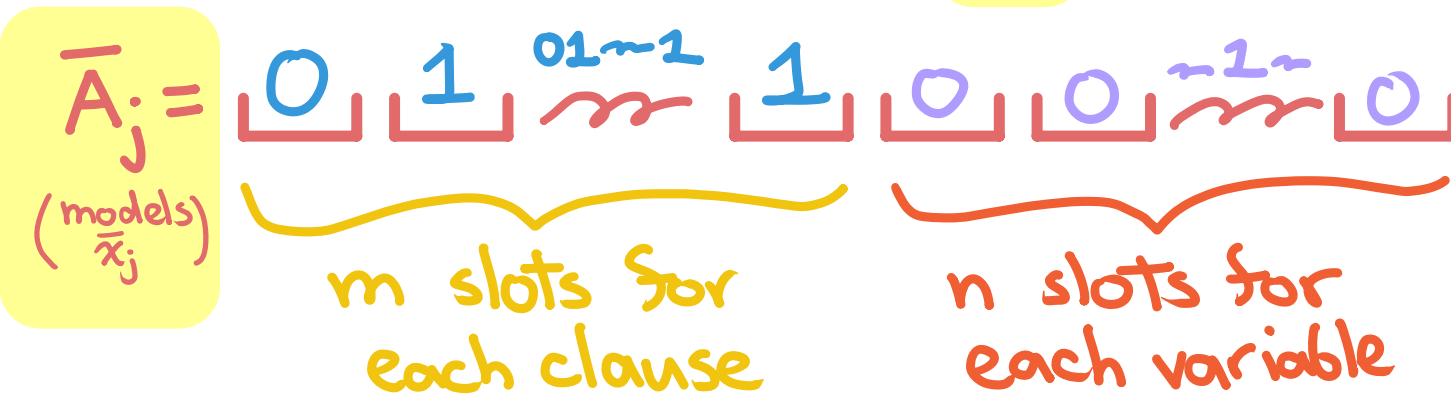
$\begin{cases} 1 & \text{if } x_j \in C_i \\ 0 & \text{otherwise} \end{cases}$

Key idea: numbers are bit-strings too!

- use many digits • each digit encodes 1 constraint

2. Start making #'s:

- we use mtn digits base 4
- Similarly, for the literal $\bar{x}_j$:



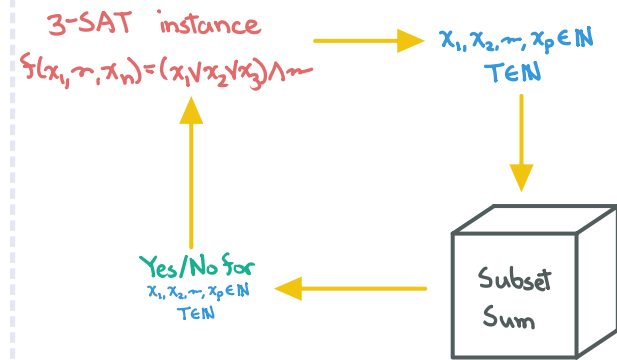
- for each clause C_i , set C_i th digit to $\begin{cases} 1 & \text{if } \bar{x}_j \in C_i, \\ 0 & \text{otherwise} \end{cases}$
- set " x_j th digit" to 1, else 0

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$



1. Recast 3SAT as "subset" problem
 $X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

clause $(x_1 \vee \bar{x}_2 \vee x_3) = \text{set } \{x_1, \bar{x}_2, x_3\} \subset X$

Goal: Find $S \subset X$ s.t.

(a) for each clause C_i , $C_i \cap S \neq \emptyset$

(b) for each x_j , S contains ^(exactly) 1 of $\{x_j, \bar{x}_j\}$

$\begin{cases} 1 & \text{if } \bar{x}_j \in C_i, \\ 0 & \text{otherwise} \end{cases}$ (not x_j)

Key idea: numbers are bit-strings too!

• use many digits • each digit encodes 1 constraint

Literals

Long #'s

$$X = \{x_1, \bar{x}_1, \dots, x_n, \bar{x}_n\} \leftrightarrow \{A_1, \bar{A}_1, \dots, A_n, \bar{A}_n\}$$

Set SCX

$$D = \sum_{x_j \in S} A_j + \sum_{\bar{x}_j \in S} \bar{A}_j$$

$$\forall \text{ constraint } C_i \leftrightarrow \forall \text{ constraint } C_i, C_i \cap S \neq \emptyset$$
$$\forall \text{ constraint } C_i \leftrightarrow \forall \text{ constraint } C_i, C_i \text{th digit of } D \geq 1$$

$$\forall \text{ variables } x_j \leftrightarrow \forall \text{ variables } x_j,$$

$$|\{x_j, \bar{x}_j\} \cap S| = 1$$

$$x_j \text{th digit of } D = 1$$

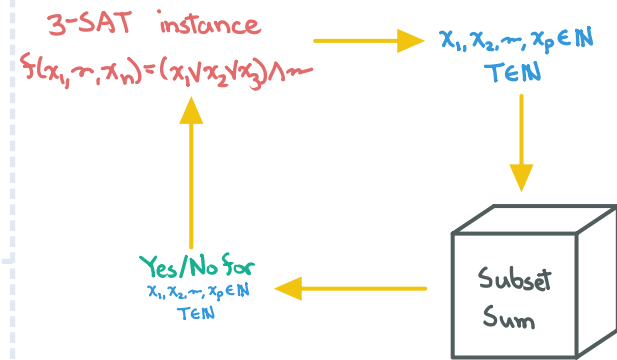
still one key diff. from subset sum...

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$



1. Recast 3SAT as "subset" problem
 $X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

clause $(x_1 \vee \bar{x}_2 \vee x_3) = \text{set } \{x_1, \bar{x}_2, x_3\} \subset X$

Goal: Find SCX st.

(a) for each clause C_i , $C_i \cap S \neq \emptyset$

(b) for each x_j , S contains ^(exactly) 1 of $\{x_j, \bar{x}_j\}$

2. Start making #'s:

• we use mtn digits base 4

• for the literal x_j :

$A_j = \underbrace{0 \ 1 \ 0 \ 1}_{m \text{ slots for each clause}} \underbrace{0 \ 0 \ 1 \ 0}_{n \text{ slots for each variable}}$

(models x_j)

$01 \sim 1$ (not $\bar{x}_j$)

$\sim 1 \sim 0$

• for each clause C_i , set C_i th digit to 1 if $x_j \in C_i$, else 0

• set " x_j th digit" to 1, else 0

Similar for the literal $\bar{x}_j$

Key idea: numbers are bit-strings too!

• use many digits • each digit encodes 1 constraint

Literals

Long #'s

$$X = \{x_1, \bar{x}_1, \dots, x_n, \bar{x}_n\} \leftrightarrow \{A_1, \bar{A}_1, \dots, A_n, \bar{A}_n\}$$

Set SCX

$$D = \sum_{x_j \in S} A_j + \sum_{\bar{x}_j \in S} \bar{A}_j$$

$$\forall \text{ constraint } C_i, \quad C_i \cap S \neq \emptyset$$

$$\forall \text{ constraint } C_i, \quad C_i \text{th digit of } D \geq 1$$

$$\forall \text{ variables } x_j, \quad |\{x_j, \bar{x}_j\} \cap S| = 1$$

$$\forall \text{ variables } x_j, \quad x_j \text{th digit of } D = 1$$

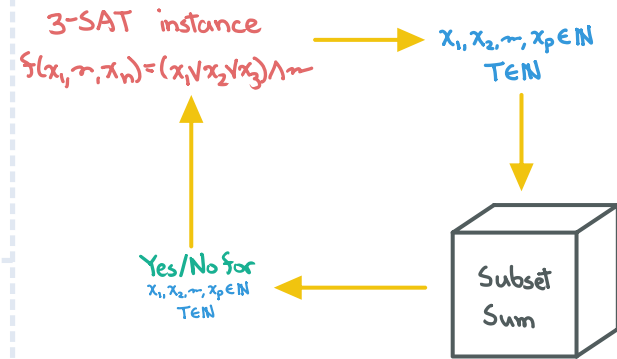
want to replace "≥" w/ "="

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
T=52



1. Recast 3SAT as "subset" problem
X = literals $\{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

clause $(x_1 \vee \bar{x}_2 \vee x_3) = \text{set } \{x_1, \bar{x}_2, x_3\} \subset X$

Goal: Find SCX st.

Ⓐ for each clause C_i , $C_i \cap S \neq \emptyset$

Ⓑ for each x_j , S contains ^(exactly) 1 of $\{x_j, \bar{x}_j\}$

2. Start making #'s:

• we use mtn digits base 4

• for the literal x_j :

$$A_j = \underbrace{0 \ 1 \ 0 \ 1}_{m \text{ slots for each clause}} \underbrace{0 \ 0 \ 1 \ 0}_{n \text{ slots for each variable}}$$

(models x_j)

• for each clause C_i , set C_i th digit to 1 if $x_j \in C_i$ (not $\bar{x}_j$), else 0

• set " x_j th digit" to 1, else 0

Similar for the literal $\bar{x}_j$

$\forall$ constraint $C_i, \leftrightarrow$
 $C_i \cap S \neq \emptyset$

$\forall$ constraint C_i ,
 C_i th digit of $D \geq 1$

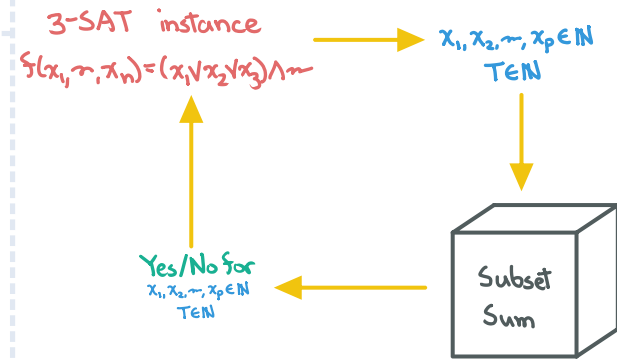
How to fix?

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
 (decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$



1. Recast 3SAT as "subset" problem

$X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

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Goal: Find $S \subset X$ st.

(a) for each clause $C_i, C_i \cap S \neq \emptyset$

(b) for each x_j, S contains ^(exactly) 1 of $\{x_j, \bar{x}_j\}$

2. Start making #'s:

• we use mtn digits base 4

• for the literal x_j :

$A_j = \underbrace{0 \ 1 \ 1 \ 0 \ 0 \ 0}_{\text{m slots for each clause}} \underbrace{0 \ 1 \ 1 \ 0 \ 0 \ 0}_{\text{n slots for each variable}}$
 (models x_j)

• for each clause C_i , set C_i th digit to 1 if $x_j \in C_i$, else 0
 (not $\bar{x}_j$)

• set " x_j th digit" to 1, else 0

Similar for the literal $\bar{x}_j$

$\forall \text{ constraint } C_i, \leftrightarrow \forall \text{ constraint } C_i, C_i \cap S \neq \emptyset$

Easy fix: "free padding"

for constraint C_i , create two copies of:

$B_i = 00 \sim 0100 \sim 0$
 $\uparrow$
 $C_i \text{th digit}$

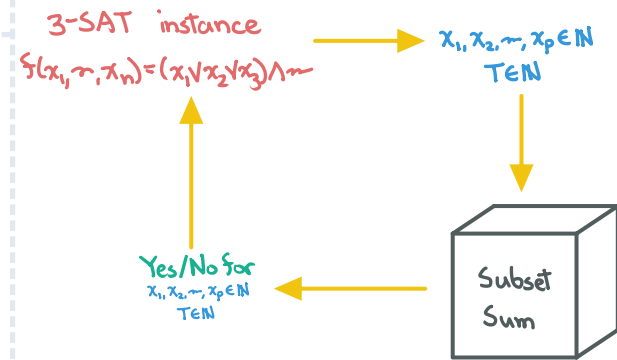
lets you increase $C_i \text{th digit}$ by 1 or 2

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
 (decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$



1. Recast 3SAT as "subset" problem

$X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$

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(b) for each x_j , S contains ^(exactly) 1 of $\{x_j, \bar{x}_j\}$

2. Start making #'s:

• we use mtn digits base 4

• for the literal x_j :

$A_j = \boxed{0} \boxed{1} \overline{01 \sim 2} \boxed{1} \boxed{0} \boxed{0} \overline{\sim 1 \sim 2} \boxed{0}$
 (models) x_j $m \text{ slots for each clause}$ $n \text{ slots for each variable}$

• for each clause C_i , set $C_i \text{th digit}$ to 1 if $x_j \in C_i$ (not $\bar{x}_j$) else 0

• set " $x_j \text{th digit}$ " to 1, else 0

Similar for the literal $\bar{x}_j$

Key idea: numbers are bit-strings too!

• use many digits • each digit encodes 1 constraint

Literals

Long #'s

$X = \{x_1, \bar{x}_1, \dots, x_n, \bar{x}_n\} \leftrightarrow \{A_1, \bar{A}_1, \dots, A_n, \bar{A}_n\}$
and $\{B_1, B_1, \dots, B_m, B_m\}$
(padding per-clause)

let $T = \underbrace{33\dots3}_m \underbrace{11\dots1}_n$
m clauses n variables

for subset of A_i 's, $\bar{A}_i$'s, B_i 's summing to D :

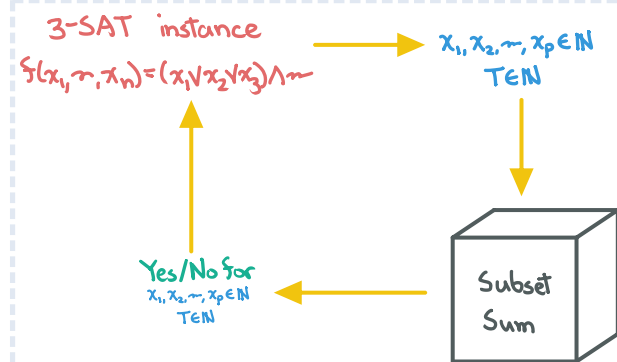
- C_i th digit of $D = 3$ only if D include $A_j/\bar{A}_j$ for some $x_j/\bar{x}_j$ in C_i (b/c of padding)
- x_j th digit of $D = 1 \Leftrightarrow$ includes (exactly) one of $A_j/\bar{A}_j$

Subset Sum

Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$

Goal: Find a subset of x_i 's that sum to T
(decision version: decide if such a subset sum exists)

e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T = 52$



1. Recast 3SAT as "subset" problem
 $X = \text{literals } \{x_1, \bar{x}_1, x_2, \bar{x}_2, \dots, x_n, \bar{x}_n\}$
clause $(x_1 \vee \bar{x}_2 \vee x_3) = \text{set } \{x_1, \bar{x}_2, x_3\} \subset X$

Goal: Find $S \subset X$ st.

- Ⓐ for each clause C_i , $C_i \cap S \neq \emptyset$
- Ⓑ for each x_j , S contains (exactly) 1 of $\{x_j, \bar{x}_j\}$

2. Start making #'s:

- we use mtn digits base 4
- for the literal x_j :

$A_j = \underbrace{01\dots1}_{m \text{ slots for each clause}} \underbrace{0\dots0}_{n \text{ slots for each variable}}$
(models x_j)

- for each clause C_i , set C_i th digit to 1 if $x_j \in C_i$, else 0
 - set " x_j th digit" to 1, else 0
- Similar for the literal $\bar{x}_j$

Theorem: A polytime algo for subset-sum implies a polytime algo for SAT

Subset Sum
 Input: $x_1, x_2, \dots, x_n \in \mathbb{N}$
 Goal: Find a subset of x_i 's that sum to T
 (decision version: decide if such a subset sum exists)
 e.g. 14, 13, 17, 7, 18, 18, 10, 4, 11, 10
 $T=52$

Literals $X = \{x_1, \bar{x}_1, \dots, x_n, \bar{x}_n\} \leftrightarrow$ Long #'s $\{A_1, \bar{A}_1, \dots, A_n, \bar{A}_n\}$
 and $\{B_1, \bar{B}_1, \dots, B_m, \bar{B}_m\}$

3-SAT instance

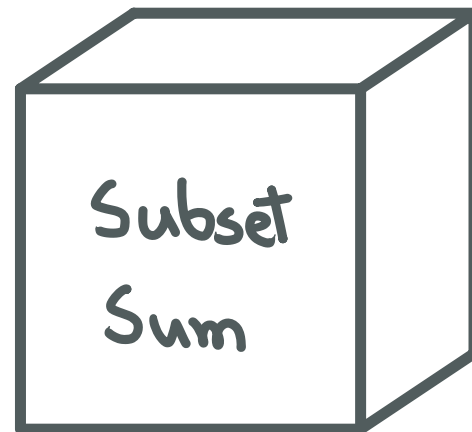
$$\mathcal{S}(x_1, \dots, x_n) = (x_1 \vee x_2 \vee x_3) \wedge \dots$$

$T = \underbrace{33 \sim 3}_{m \text{ clauses}} \underbrace{11 \sim 1}_{n \text{ variables}}$

$x_1, x_2, \dots, x_p \in \mathbb{N}$

$T \in \mathbb{N}$

Yes/No for
 $x_1, x_2, \dots, x_p \in \mathbb{N}$
 $T \in \mathbb{N}$



Key idea: numbers are bit-strings too!
 — use many digits
 — each digit encodes 1 constraint

