Randomness and Computation
or, “Randomized Algorithms”

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Logical Formulae and the “satisfiability” question

Definition
Suppose we have a collection of (propositional) logical variables $x_1, \ldots, x_n$ for varying $n$.

A literal is any expression which is either $x_i$ or $\bar{x}_i$, for some $i \in [n]$.

A clause is any disjunction of a number of literals.

We say a propositional formula $\phi : \{0, 1\}^n \rightarrow \{0, 1\}$ is in Clausal Normal Form (CNF) if it is of the form

$$C_1 \land C_2 \ldots \land C_h,$$

where every $C_j$ is a clause.

The formula $\phi : \{0, 1\}^n \rightarrow \{0, 1\}$ is in $k$-CNF if it is in CNF and every clause contains exactly $k$ literals.

The SAT problem, $k$-SAT problem is the problem of examining a given CNF (or $k$-CNF) expression and deciding whether or not it has a satisfying assignment.
Examples of SAT, \(k\)-SAT

Example of a SAT question:

\[(x_1 \lor x_8 \lor \bar{x}_6) \land (\bar{x}_4 \lor \bar{x}_7) \land (x_5 \lor x_7 \lor x_4 \lor x_2).\]

- For the formula above, easy to see there is a (many) satisfying assignment(s) to the \(x_i\) variables (any with \(x_1 = 1, x_4 = 0, x_2 = 1\) would do, for example).

- In general, the SAT problem is NP-complete (we believe there is no polynomial-time algorithm).

Example of a 2-SAT question:

\[(x_1 \lor \bar{x}_2) \land (\bar{x}_1 \lor \bar{x}_3) \land (x_1 \lor x_2) \land (x_4 \lor \bar{x}_3) \land (x_4 \lor \bar{x}_1).\]

- There is a polynomial-time algorithm (either randomized, as we see today, or deterministic) to solve 2-SAT.

- The 3-SAT problem, and \(k\)-SAT for all \(k > 3\), are all NP-complete.
2-SAT Randomized Algorithm

We will design a simple randomized algorithm for 2-SAT, and analyse its performance by analogy to a Markov chain.

Algorithm 2SATRANDOM\((n; C_1 \land C_2 \land \ldots \land C_\ell)\)

1. Assign arbitrary values to each of the \(x_i\) variables.
2. \(t \leftarrow 0\)
3. while \((t < 2mn^2\) and some clause is unsatisfied) do
4. Choose an arbitrary \(C_h\) from all unsatisfied clauses;
5. Choose one of the 2 literals in \(C_h\) uniformly at random and flip the value of its variable;
6. if (we end with a satisfying assignment) then
7. return this assignment to the \(x_1, \ldots x_n\) else
8. return FAILED.

Note that arbitrary is very different from random.

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2-SAT Randomized Algorithm

Imagine Algorithm 2SATRANDOM running on our 2SAT example, with the initial assignment being $x_i = 0$ for all $i \in [n]$.

$$(x_1 \lor \bar{x}_2) \land (\bar{x}_1 \lor \bar{x}_3) \land (x_1 \lor x_2) \land (x_4 \lor \bar{x}_3) \land (x_4 \lor \bar{x}_1).$$

► Then $(x_1 \lor x_2)$ is the sole unsatisfied clause.
► Flipping the value of $x_2$ (say) from 0 to 1, will ensure that $(x_1 \lor x_2)$ now becomes satisfied.
► However, making this flip would also change the assignment for $(x_1 \lor \bar{x}_2)$, making this clause now unsatisfied.
► This is a balanced consequence overall (number of satisfied clauses stays the same). Note that a similar scenario would arise had we instead flipped $x_1$ to satisfy $(x_1 \lor x_2)$ (we would have violated $(x_4 \lor \bar{x}_1)$ in that case).

However, there are examples where a flip might end up violating many clauses. So it’s not so helpful for us to use “number of clauses satisfied” as our measure of progress.
Consider an (unknown so far) satisfying assignment $S \in \{0, 1\}^n$ that makes our 2SAT formula $\phi$ true (satisfies all the clauses).

Our “measure of progress” will be the number of indices $k$ such that $x_k = S_k$, $(x_1, \ldots, x_n)$ being the current assignment.

We will analyse the expected number of steps before $(x_1, \ldots, x_n)$ becomes $S$.

▶ This of course assumes the formula $\phi$ has some satisfying assignment.

▶ Note that if $\phi$ does not have any satisfying assignment, Algorithm 2SATRANDOM always returns FAILED (as it should).
To analyse the behaviour of Algorithm 2SATRANDOM when given a 2CNF formula $\phi$ that is satisfiable, we need some definitions.

**Definition**
For our given satisfiable 2SAT formula $\phi$, let $S$ be some satisfying assignment for $\phi$.

Let $(x_1^t, \ldots, x_n^t)$ denote the assignment to the logical variables after the $t$th iteration of the loop at 3.

Let $X_t$ denote the number of variables of the assignment $(x_1^t, \ldots, x_n^t)$ having the same value as in $S$.

We work with the $X_t$ variable mainly, and bound the time before it reaches the value $n$. 
2-SAT Randomized Algorithm - Analysis

Some observations:

▶ If $X_t$ ever hits the value 0, and $\phi$ is unsatisfied, we are guaranteed that at the next step, $X_{t+1} = 1$.

$$\Pr[X_{t+1} = 1 \mid ((X_t = 0) & \phi \text{ unsat})] = 1.$$

▶ Alternatively, suppose $X_t = j$ for some value $j \in \{1, \ldots, n-1\}$ and that $\phi$ is unsatisfied.

Then on any of the individual unsatisfied clauses, we know the current assignment $x^t$ must differ from $S$ on at least one of the two variables. Hence with probability at least $1/2$, we will increase the value of $X_t$ by 1 (and with probability at most $1/2$ decrease the value of $X_t$ by $1/2$).

$$\Pr[X_{t+1} = j + 1 \mid ((X_t = j) & \phi \text{ unsat})] \geq 1/2;$$
$$\Pr[X_{t+1} = j - 1 \mid ((X_t = j) & \phi \text{ unsat})] \leq 1/2.$$
We want to imagine the progress of 2SATRANDOM as a Markov chain on the states 0, 1, ..., n. Our concern is bounding the expected number of steps $t$ for $X_t$ to hit the state $n$ (from an arbitrary starting point).

- Markov chains should be memoryless, and this is problematic.
- The value for $\Pr[X_{t+1} = j + 1 \mid (X_t = j) \& \phi \text{ unsat}]$ can be 1/2 or 1 depending on how many variables of the chosen clause currently disagree with $S$. This may have been affected by earlier flips done by the algorithm.
- We choose to “tweak” the probabilities and study the process on $\{0, 1, \ldots, n\}$ where we have to make the process memoryless. We consider a slightly different process on $\{0, 1, 2, \ldots, n\}$ defined by the variable $Y_t$ on the next slide.
Consider the Markov chain $Y_0, Y_1, \ldots, Y_t, \ldots$ such that
\[
Y_0 = X_0; \\
\Pr[Y_{t+1} = 1 \mid ((Y_t = 0) \& \phi \text{ unsat})] = 1; \\
\Pr[Y_{t+1} = j + 1 \mid ((Y_t = j) \& \phi \text{ unsat})] = 1/2; \\
\Pr[Y_{t+1} = j - 1 \mid ((Y_t = j) \& \phi \text{ unsat})] = 1/2.
\]

Clearly the expected number of steps for $X_t$ to hit $n$ is $\leq$ that for $Y_t$. 

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For any $j = 0, \ldots, n - 1$, define $h_j$ to be the expected number of steps to hit $n$ starting from $j$.

- $h_j$ is the $h_{j,n}$ measure from lecture 14 (we omit $n$ because this is the same target for each $j$);

- Clearly, the expected number of steps for 2SATRANDOM to find a satisfying assignment is at most $\max_j h_j$ (may well be better).

- We will bound $h_j$ for every $j = 0, 1, \ldots, n$. 


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2-SAT Randomized Algorithm - Analysis

We have $h_n = 0$ and $h_0 = h_1 + 1$ for the “end cases”.

We will use $Z_j$, for $0, 1, \ldots, n - 1$, to be the random variable for the “number of steps” to reach $n$ from $j$ ($h_j$ will be $E[Z_j]$).

For $j = 1, \ldots, n - 1$, recalling the steps of the “random walk”, and using linearity of expectation:

$$E[Z_j] = \frac{1}{2}(E[Z_{j-1}] + 1) + \frac{1}{2}(E[Z_{j+1}] + 1),$$

$$h_j = \frac{1}{2}(h_{j+1} + 1 + h_{j-1} + 1)$$

This gives us the following system of equations:

$$h_0 = h_1 + 1$$
$$h_j = \frac{h_{j-1} + h_{j+1}}{2} + 1 \quad \text{for } j = 1, \ldots, n - 1$$
$$h_n = 0$$
2-SAT Randomized Algorithm - Analysis

We show by induction that for $j = 0, \ldots, n - 1$,

$$h_j = h_{j+1} + 2j + 1.$$  

Proof.

**Base case:** If $j = 0$, $2j + 1 = 1$, and we were given $h_0 = h_1 + 1$.

**Inductive step:** Suppose this was true for $j = k - 1$ (we had $h_{k-1} = h_k + 2(k - 1) + 1$, this is our (IH)). Now consider $j = k$.

By the “middle case” of our system of equations,

$$h_k = \frac{h_{k-1} + h_{k+1}}{2} + 1$$

$$= \frac{h_k + 2(k - 1) + 1}{2} + \frac{h_{k+1}}{2} + 1 \quad \text{by our (IH)}$$

$$= \frac{h_k}{2} + \frac{h_{k+1}}{2} + \frac{2k + 1}{2}$$

Subtracting $\frac{h_k}{2}$ from each side, this is equivalent to

$$h_k = h_{k+1} + 2k + 1,$$

as claimed.

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Lemma (Lemma 7.1)

Assume that the given 2CNF formula has a satisfying assignment, and that 2SATRANDOM is allowed to carry out as many iterations as it wants to find a satisfying assignment. Then the expected number of iterations of 3. to find that assignment at most $n^2$.

Proof.

We showed that the expected number of iterations is at most $\max_{j=0,\ldots,n-1}\{h_j\}$. We now know the max is $h_0$.

Applying $h_k = h_{k+1} + 2k + 1$ iteratively, we have

\[
h_0 = \sum_{k=0}^{n-1} (2k + 1) + h_n
\]

\[
= 2 \sum_{k=0}^{n-1} k + n + 0
\]

\[
= 2 \frac{(n-1)n}{2} + n = n^2.
\]
Probability of failure

**Theorem**

Algorithm \textsc{2SATRandom} is parametrized by \( m \), and the algorithm will perform up to \( mn^2 \) iterations of the loop.

Then, when there is a satisfying assignment for \( \phi \), the probability that \textsc{2SATRandom} does not discover one, is at most \( 2^{-m} \).

**Proof.**

Markov’s Inequality.
Reading and Doing

Reading

- This material is from Section 7.1 of [MU].
- Section 7.4 from the book is interesting (we were looking at a random walk on the line today).

Doing

- Exercises 7.3 and 7.7 from [MU].