What will we do today?

- Non-uniform complexity
- Circuit complexity
- TMs that take advice
- The Karp-Lipton Theorem
Non-uniformity

- "Uniform": the algorithm is the same, regardless of the input size
- "Non-uniform": there can be different algorithms for different input sizes
Boolean circuits are very similar to propositional formulas.

Directed acyclic graphs (instead of trees)

We view binary strings as truth assignments.

Example: \( (\neg x_1 \lor x_2) \land (\neg x_2 \lor x_3) \), \( x = 010 \), and \( \alpha_x = \{ x_1 \mapsto 0, x_2 \mapsto 1, x_3 \mapsto 0 \} \)
Boolean circuits

Definition (Circuits)

An *n*-input single-output Boolean circuit $C$ is a directed acyclic graph with:
- $n$ sources (nodes with no incoming edges), labelled 1 to $n$, and
- one sink (a node with no outgoing edges).

All non-source vertices are called *gates*, and are labelled with $\wedge$, $\lor$, or $\neg$:
- $\wedge$-gates and $\lor$-gates have in-degree 2 (exactly two incoming edges),
- $\neg$-gates have in-degree 1 (exactly one incoming edge).

If $C$ is an *n*-input single-output Boolean circuit and $x \in \{0, 1\}^n$ is a string, then the output $C(x)$ of $C$ on $x$ is defined by plugging in $x$ in the source nodes and applying the operators of the gates, and taking for $C(x)$ the resulting value in $\{0, 1\}$ of the sink gate.
Definition (Circuit families)
Let \( t : \mathbb{N} \to \mathbb{N} \) be a function. A \( t(n) \)-size circuit family is a sequence \( \{C_n\}_{n \in \mathbb{N}} \) of Boolean circuits, where each \( C_n \) has \( n \) inputs and a single output, and \( |C_n| \leq t(n) \) for each \( n \in \mathbb{N} \).

Definition (SIZE(\( t(n) \)))
Let \( t : \mathbb{N} \to \mathbb{N} \) be a function. A language \( L \subseteq \{0, 1\}^* \) is in \( \text{SIZE}(t(n)) \) if there exists a constant \( c \in \mathbb{N} \) and a \((c \cdot t(n))\)-size circuit family \( \{C_n\}_{n \in \mathbb{N}} \) such that for each \( x \in \{0, 1\}^* \):

\[
x \in L \quad \text{if and only if} \quad C_n(x) = 1, \text{ where } n = |x|.
\]
The complexity class $P/poly$

Definition ($P/poly$)

$$P/poly = \bigcup_{c \geq 1} \text{SIZE}(n^c).$$

- In other words, $P/poly$ is the class of all decision problems that can be decided by a polynomial-size circuit family.
(We consider only decision problems \( L \subseteq \{0, 1\}^* \)—i.e., binary alphabets.)

Theorem

\( \text{P} \subseteq \text{P/poly} \).

Main idea:

- Like in the proof of the Cook-Levin Theorem, we encode polynomial-time computation in logic.
- Instead of using new, fresh variables we use nodes in the Boolean circuit (to encode tape contents, tape head positions, etc).

In fact, \( \text{P} \not\subseteq \text{P/poly} \) (you will show this in the homework).
Turing machines that take advice

- We can characterize \( P/poly \) (or more generally, non-uniform complexity classes) also using TMs.

- The algorithm might differ per input size \( n \), so we will have to give the TM something that depends only on the input size.

- This is called advice.
Advice characterization of P/poly

**Definition (TIME(t(n))/a(n))**

Let $t, a : \mathbb{N} \rightarrow \mathbb{N}$ be functions. The class $\text{DTIME}(t(n))/a(n)$ of languages decidable by $O(t(n))$-time Turing machines with $a(n)$ bits of advice contains every decision problem $L \subseteq \{0, 1\}^*$ such that:

- there exists a sequence $\{\alpha_n\}_{n \in \mathbb{N}}$ with $\alpha_n \in \{0, 1\}^{a(n)}$ for each $n \in \mathbb{N}$ and an $O(t(n))$-time deterministic Turing machine $M$ such that for each $x \in \{0, 1\}^*$:

  $$x \in L \text{ if and only if } M(x, \alpha_n) = 1, \text{ where } n = |x|.$$
Advice characterization of P/poly (ct’d)

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<th>Theorem</th>
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<td>P/poly = \bigcup_{c,d \geq 1} \text{DTIME}(n^c)/n^d.</td>
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- **Main idea (for “⊆”):**
  - Use a description of $C_n$ as $\alpha_n$, and then compute $C_n(x)$ in polynomial time

- **Main idea (for “⊇”):**
  - The computation of $M(x, \alpha_n)$ on inputs $x \in \{0, 1\}^n$ can be encoded as a polynomial-size circuit $D_n(\cdot, \alpha_n)$, using ideas from the proof of the Cook-Levin Thm
  - The circuit $C_n$ is $D_n$ with $\alpha_n$ “hardwired in”
**Definition**

A circuit family \( \{C_n\}_{n \in \mathbb{N}} \) is **P-uniform** if there exists a polynomial-time deterministic TM that on input \( 1^n \) outputs a description of \( C_n \), for each \( n \in \mathbb{N} \).

**Theorem**

A decision problem \( L \subseteq \{0, 1\}^* \) is in P if and only if decidable by a P-uniform circuit family \( \{C_n\}_{n \in \mathbb{N}} \).
The Karp-Lipton Theorem

- Question: is SAT decidable by polynomial-size circuits (is it in P/poly)?
  - Perhaps by allowing the algorithm to change per input size, this might work
  - The answer: No (assuming that the PH does not collapse)

Theorem (Karp, Lipton 1980)

If $\text{NP} \subseteq \text{P/poly}$, then $\Sigma_2^p = \Pi_2^p$. 
Proof of the Karp-Lipton Thm

The general argument

- Suppose that $\text{NP} \subseteq \text{P/poly}$.
- We show that then $\Pi^p_2 \subseteq \Sigma^p_2$, by showing $\Pi_2\text{SAT} \in \Sigma^p_2$.
- We use the following lemma to swap the order of the quantifiers:

**Lemma**

If $\text{NP} \subseteq \text{P/poly}$, then there exists a polynomial-time algorithm that:

- takes polynomial-length advice, and
- given a propositional formula $\varphi$:
  - if $\varphi$ is unsatisfiable, it outputs 0;
  - if $\varphi$ is satisfiable, it outputs a satisfying truth assignment $\alpha$ for $\varphi$.

- Idea behind the proof of the lemma: use self-reducibility of SAT.
Proof of the Karp-Lipton Thm

Completing the proof

Take an arbitrary instance of $\Pi_2$SAT: $\varphi = \forall \bar{u}. \exists \bar{v}. \psi(\bar{u}, \bar{v})$.

Let $q$ be the polynomial bounding the size of the advice $\{\alpha_n\}_{n \in \mathbb{N}}$ that can be used to compute satisfying assignments for SAT, in polynomial time with TM $\mathcal{M}$.

$\varphi = \forall \bar{u}. \exists \bar{v}. \psi(\bar{u}, \bar{v}) \in \Pi_2$SAT if and only if for all $\bar{z} \in \{0,1\}^m$, $\psi[\bar{u} \mapsto \bar{z}] \in \text{SAT}$.

This is the case if and only if:

$\exists$ there exists some $\bar{w} \in \{0,1\}^{q(n)}$ such that

$\forall$ for all $\bar{z} \in \{0,1\}^m$

poly $\mathcal{M}$ uses $\bar{w}$ as advice to output the assignment $\gamma$ on input $\psi[\bar{u} \mapsto \bar{z}]$ and $\gamma$ satisfies $\psi[\bar{u} \mapsto \bar{z}]$

Key: we check that $\gamma$ is correct; because we don’t know whether $\bar{w}$ is the right advice

Thus, $\Pi_2$SAT $\in \Sigma^p_2$, and therefore $\Pi^p_2 = \Sigma^p_2$. 
Recap

- Non-uniform complexity
- Circuit complexity
- TMs that take advice
- The Karp-Lipton Theorem: if $\text{NP} \subseteq \text{P/poly}$, then $\Sigma_2^p = \Pi_2^p$
Next time

- Probabilistic algorithms
- Complexity classes BPP, RP, coRP, ZPP