Course contents

- Classical resources: Time, Space, Non-determinism.
- Alternation & the Polynomial Hierarchy.
- Non-uniform complexity & Lower bounds.
- Randomness and its power.
- Proofs, Interaction, Knowledge.
- Quantum computation.

Complexity Theory

Basic iteration:

- Identify resource; pick a gross bound on resource.
- Find points = problems.
- Draw arrows (reductions). $A \to B$, or $A \leq B$ if A reduces to B.
- In some cases rule out arrows.

Hopefully, get a map of all computational problems and complexities involved.

Classically ...

Resources Time, Space, Non-determinism.

Stopping points Logarithmic, Polynomial, Exponential.

Reductions?

- Karp vs. Turing.
- Logspace vs. Polynomial time.

Turing reductions & Relativization

Definition: $L_1 \leq_T^p L_2$ if there exists a polynomial time Turing machine M that with access to an oracle for L_2 can solve the problem L_1.

Languages vs. Problems Problems are general functions; Languages are Boolean functions. Turing reductions work generally. Their most powerful usage is to reduce general problems to languages.

Exercise Reduce SEARCH-SAT to SAT.

Relativization M above is an oracle Turing machine since it invokes an oracle O occasionally. Notation to describe this duo: M^O. Here our focus was on what can O be used to do, when we vary M. In relativization, we often fix M (or the class it comes from) and vary O to see what can be done. Will see more next lecture.

Food for thought Why need Karp reductions? (Hint: two famed classes would be indistinguishable under Turing reductions.)

Classical classes

- Logarithmic space L.
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- Polynomial time P.
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- Polynomial space $PSPACE$.
- Exponential time E/EXP.
- etc.

Classical classes

- Logarithmic space L - ?
- Nondeterministic Logspace NL - STCON.
- Polynomial time P - CktVal.
- Nondeterministic Polytime NP - SAT.
- And much more to be inserted here.
- Polynomial space $PSPACE$ - QSAT, Games.
- Exponential time E/EXP - Succinct SAT, Chess.
- etc.

Basic results

- Time Hierarchy theorem.
- Space Hierarchy theorem.
- Blum's speedup theorem.
- Any one remembers exact form?
- Diagonalization - Tool #1 in proving absence of arrows.

Food for thought

- Given language in NP, can we decide if it is in P or not?
- Is every language in NP either in P or NP-complete?
- Is there a NTIME hierarchy theorem? What goes wrong with the usual proof?
- Is linear time a reasonable notion? How about nearly linear time?

Some other basic results

- Time(t) in NTime(t) in Space(t) (actually can do a bit better)!
- Space(s) in Time(2^s).
- Technically harder results:
  - NSPACE(s) in SPACE(s^2).
  - NSPACE(s) in coNSPACE(O(s)).
- Will prove above later today.

Big questions

P = NP?

1. Belief: P $\neq$ NP.
2. Stronger belief: NP $\neq$ co-NP.
3. Weaker beliefs:
   (a) P $\neq$ PSPACE.
   (b) SAT not in L.
   (c) SAT not in nearly Linear Time.
4. Another belief: L $\neq$ P.

We know at least one of 3(a) or 4 is true!

Will show one more such statement (hopefully).

Rest of lecture

Quick Review of

- Savitch's theorem.
- Immerman-Szelepscenyi theorem.

Savitch's theorem

Thm: For all space constructible $s(n) \geq \log n$, NSPACE$(s(n) \subseteq$ SPACE$s^2(n)$.

Simplifying assumptions:

- Suffices to consider the case $s = \log n$.
- Suffices to show that STCON can be solved in space $O(\log^2 n)$.
- STCON:

  Given: Directed graph G, vertices s, t.
  YES instances: There is a directed path from s to t in G.

- Suffices to let n be power of 2: $n = 2^k$.

STCON Algorithm

- Let A be the adjacency matrix of G.
- Suffices to compute A^n, where $A \cdot B$ denote Boolean matrix multiplication and $A^n = A \cdot A^{n-1}$.

Basic Lemma on Space

Basic Lemma: If $f, g : \{0,1\}^n \rightarrow \{0,1\}^n$ can be computed in space s_1 and s_2 respectively, then $f \circ g : \{0,1\}^n \rightarrow \{0,1\}^n$ can be computed in space $s_1 + s_2$ (no big-Ohs!).

Proof: Omitted.

Lemma: Given A, the matrix A^{2^ℓ} can be computed in space $\ell \log n$.

Proof: Induction using Basic Lemma.

Savitch's theorem follows.

Immerman-Szelepscenyi Theorem

Thm: For all space constructible $s(n) \geq \log n$, co-NSPACE$(s(n)) \subseteq$ NSPACE$O(s(n))$.

Idea:

- Suffices to prove co-STCON in NL.
- Key quantities:

  $\Gamma_\ell(s) = \{v \in V | \exists$ path w. length $\leq \ell$ from s to

  $$\mathrm{COUNT}(s, \ell) = |\Gamma_\ell(s)|$$

- Central subroutine: CHECK$(u, \ell, COUNT)$.

  Guarantee: If COUNT $= \mathrm{COUNT}(s, \ell - 1)$, then OUTPUT $=$ TRUE iff there is no path from s to u of length $\leq \ell$.

NL=coNL: Proof

Lemma 1: co-STCON in NL if CHECK in NL.

Proof:

- Inductively, compute $\mathrm{COUNT}(s, \ell)$ given $\mathrm{COUNT}(s, \ell - 1)$ as follows:
  - Initialize $\mathrm{COUNT} s, \ell = 0$.
  - For each $u \in V$ guess if $v \in \Gamma_\ell(s)$.
  - If Guess=YES, verify the guess and increment $\mathrm{COUNT}(s, \ell - 1)$.
  - If Guess=NO, use CHECK$(u, \ell, \mathrm{COUNT}(s, \ell - 1))$ to verify guess.

NL=coNL: Proof (contd.)

Lemma 2: CHECK$(u, \ell, COUNT) \in$ NL.

Algorithm:

- Initialize COUNT-SO-FAR = 0;
- For every $v \in V$ do:
  - Guess if $v \in \Gamma_{\ell-1}(s)$.
  - If Guess= NO, do nothing;
  - If Guess= YES, (1) verify guess, (2) increment COUNT-SO-FAR, and (3) verify (v, u) is not an edge.
- Verify COUNT-SO-FAR = COUNT.
- Return(TRUE).

"Verify COND" $\equiv$ Abort if COND is FALSE.

Next lecture

- Relativization.
- Baker Gill Solovay theorem.
- ?