Today

- ASPACE vs. TIME
- ATIME vs. SPACE
- Perspective on PSPACE
- Fortnow's Time/Space lower bound on SAT.

Recall Alternation

- Turing machine with two special states $\exists$ and $\forall$, each with two outgoing transitions.
- $\exists$ state accepts if one outgoing path accepts.
- $\forall$ state accepts if both paths accept.
- Computation tree determines resources:
  - Time
  - Space
  - Alternation

Fundamental classes

Notation: ATISP$[a, t, s]$.

- ATIME(t)
- ASPACE(s)
- Σ_i^P =ATISP$[i, poly, poly]$ starting in existential quantifier.
- Π_i^P =ATISP$[i, poly, poly]$ starting in universal quantifier.
- PH $= \cup_i \Sigma_i^P = \cup_i \Pi_i^P$.

Last assertion follows from:

$$\Sigma_i^P \subseteq \Pi_{i+1}^P, \quad Pi_i^P \subseteq \Sigma i + 1^P$$

Theorem 1: ATIME vs. SPACE

Lemma 1.1: ATIME(s) $\subseteq$ SPACE(s).

Proof: Straightforward simulation, using one extra tape to record stack of $\exists$'s and $\forall$'s.

Lemma 1.2: SPACE(s) $\subseteq$ ATIME(s^2).

Proof: As in proof of Savitch's theorem. Let TM A use space s on input x. Make Atime(s^2) machine M(c1,c2,t) to check if A goes from configuration c1 to c2 in t steps as follows:

M(c1,c2,t):
GUESS c3 = config at time t/2
FORALL check M(c1,c3,t/2)
check M(c3,c2,t/2).

Theorem: ATIME(poly) = PSPACE.

Theorem 2: ASPACE vs. TIME

Lemma 2.1: ASPACE(s) in TIME($2^{O(s)}$)

Proof: Make circuit corresponding to ASPACE computation:

- Gates = (C,i): C = config, i = time $\in [1, 2^s]$.
- Wires = $(C', i+1) \to (C, i)$ if C has arrow pointing to C'. Gates at depth 2^s with incoming arrows labelled REJ. Gates labelled ACC/REJ if configuration is accepting/rejecting. Gates label OR/AND depending on their type $\exists/\forall$ etc.
- Gives circuit of size 2^s - accepts iff computation accepts.

Theorem 2: ASPACE vs. TIME (contd.)

Lemma 2.2: Time(2^s) in ASPACE(O(s))

Proof: Suffices to build machine M that checks if A, on input x, has contents sigma on cell i of configuration after t steps.

M(i,t,sigma): GUESS r1,r2,r3 contents of cells i-1,i,i+1 at time t-1.
Verify (r1,r2,r3,sigma) is consistent
FORALL M(i-1,t-1,r1);
M(i,t-1,r2);
M(i+1,t-1,r3);

Computational philosophy

Comparing candidates for an election: Three options:

- Candidates don't get to campaign. We make our own decisions based on our own information.
- Candidates get to write a (bounded) position paper/single page ad campaign.
- Candidates are invited to debate.

What is a better system?

Computational philosophy (contd).

Computer scientist's take: How *complex* a language can the system prove membership in?

Say thesis is $x \in L$? The masses need to be convinced. How powerful can L be under these scenarios.

Model: Masses/audience as polytime computation.

- Zero input from candidates: $L \in P$.
- Fixed input from candidates: $L \in NP$.
- Full fledged debate between candidates: $L \in PSPACE$.

Debate systems

Use characterization PSPACE = ATIME(poly).

Candidates E ($\exists$) and U $\forall$:

E candidate claims $x \in L$. U candidate claims $x \notin L$. Every time TM comes to $\exists$ state, E tells us which way to go. $\forall$ state U tells us which way to go. Audience watches the debate, and at the end makes its own conclusion on whether $x \in L$ or not, based on TM's final state.

Complexity of Games

- Typical 2-person game: can evaluate if current position is already won or not; but hard to guess what will happen if we can find optimal strategies.
- For any such game (where win/loss depends only on current configuration and not on history), complexity of deciding who can win is in PSPACE.
- For some games (such as GO/Generalized Geog.), deciding who can win is PSPACE complete. (Again proven using ATIME(poly) = PSPACE.)

A PSPACE complete problem

TQBF $= \{\phi | \exists \mathbf{x}_1, \forall \mathbf{x}_2, \ldots, Q_n \mathbf{x}_n, \phi(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n$

- $\mathbf{x}_i$ vector of n-variables $x_{i,1}, \ldots, x_{i,n}$.
- ϕ - 2CNF formula on n^2 variables.
- Q_i: alternating quantifiers; $Q_i = \exists$ if i odd, and $Q_i = \forall$ if i even.

Proposition: TQBF is PSPACE complete.

Proof: Uses ATIME(poly) = PSPACE.

Power of Alternation

- Basic notion.
- Captures Time/Space differently.
- Next application shows how powerful it is.

Fortnow's theorem

For today, will use LIN to mean the class of computations in NEARLY-LINEAR TIME:

$LIN = \cup_c TIME(n(\log n)^n$.

- Belief: SAT $\notin L$.
- Belief: SAT $\notin LIN$.
- Can't prove any of the above.
- Fortnow's theorem: Both can not be false!

Proof of Fortnow's theorem

- For simplicity we'll prove that if SAT $\in \mathrm{Time}(n \log n)$ and SAT $\in L$ then we reach a contradiction.
- Won't give full proof: But rather give main steps, leaving steps as exercises.

Main ideas

- Alternation simulates small space computations in little time. (Savitch).
- If NTIME(t) in co-NTIME(t log t), then alternation is not powerful.
- Formal contradiction derived from: ATIME[a,t] $\not\subseteq$ ATIME[a-1,t/log t].

Fortnow: Step 1

Fact 1: If L in NTIME(t), and x of length n, then can construct SAT instance phi of size t(n) log t(n) such that x in L iff phi in SAT.

Reference: a 70's paper of Cook.

Proof: Left as exercise.

Fortnow: Step 2

Fix a(n) = sqrt(log n).

Fact 2: ATIME[a,t] is contained in NTIME[t $(\log t)^{2a}$]

Proof: Induction on #alternations + Fact 1.

Fortnow: Step 3

Fact 3: If SAT in L, then NTIME[t $(\log t)^{2a}$] in SPACE(log t + a log log t).

Proof: Padding

Fortnow: Step 4

Fact 4: SPACE[s] in ATISP[b,$2^{(s/b)}$,bs] in ATIME[b,$2^{(s/b)}$]

Proof: Exercise 3 of PS 1.

Whither contradiction?

- If we set b = a-1 (approximated by a in our calculations), then ...
- ATIME[a,t] is contained in ATIME[b,$2^{(logt+aglo}$ which is a contradiction.