1 Space complexity

We would like to be able to meaningfully study languages that can be computed in sub-linear space. This requires making a few variants to the Turing machine model we studied so far.

Definition 1.1 (Space complexity for languages). Let $S : \mathbb{N} \to \mathbb{N}$ be a (computable) function. A language $L \subset \{0,1\}^*$ is in space $S$ if there exists a TM $M$ which computes $L$. The TM has two tapes:

1. A read-only input tape.
2. A read-write work tape. We assume that on any input $x$, when running $M(x)$ the TM uses at most $O(S(|x|))$ many work tape cells.

The class $\text{SPACE}(S)$ is the class of all such languages.

Similar to nondeterministic time, we can also define nondeterministic space. The definition is the same, except that we allow a NTM $M$. We denote by $\text{NSPACE}(S)$ the class of all such languages.

We also define space complexity for non-boolean functions. For these, as the output is not boolean, we have to be a bit careful.

Definition 1.2 (Space complexity for functions). A function $f : \{0,1\}^* \to \{0,1\}^*$ is in (implicit) $\text{SPACE}(S)$ if

(i) $|f(x)| \leq 2^{O(S(|x|))}$.

(ii) The language $L_f = \{(x,i,a) : f(x)_i = a\}$ is in $\text{SPACE}(S)$.

These together imply that we can compute specific bits of $f(x)$ in space $S(|x|)$. In particular, specifying the coordinate $i$ requires at most space $S(|x|)$.

Some common classes of interest are:
• Polynomial space: \( \text{PSPACE} = \bigcup_{c \geq 1} \text{SPACE}(n^c) \)
• Nondeterministic polynomial space: \( \text{NPSPACE} = \bigcup_{c \geq 1} \text{NSPACE}(n^c) \)
• Logarithmic space: \( \text{LOGSPACE} = \text{SPACE}(\log n) \) (it is sometimes abbreviated as \( L \))
• Nondeterministic logarithmic space: \( \text{NLOGSPACE} = \text{NSPACE}(\log n) \) (it is sometimes abbreviated as \( \text{NL} \))

We would typically only consider space \( S(n) \geq \log n \). The reason is that most algorithms require at least that much space, for example to describe a point. Surprisingly, many algorithms can be computed in sub-linear space. For example, summing two \( n \)-bit integers can be done in space \( O(\log n) \). On the other hand, many efficient graph algorithms (such as BFS or DFS) require space linear in the number of vertices. Here are some more examples:

**Claim 1.3.** \( \text{SAT} \in \text{PSPACE} \).

*Proof.* We can enumerate the possible assignments and try each one. \( \square \)

We will later show that in fact \( \text{PH} \subset \text{PSPACE} \).

**Claim 1.4.** Let \( \text{BALANCED} = \{ x \in \{0,1\}^* : x \text{ has the same number of 0’s and 1’s} \} \). Then \( \text{BALANCED} \in \text{LOGSPACE} \).

*Proof.* Go over the input and count the number of 0’s and 1’s, then compare them. \( \square \)

The last claim is left as exercise.

**Claim 1.5.** Let \( \text{SUMEQUAL} = \{ (x, y, z) \in \{0,1\}^* : x + y = z \} \), where we consider \( x, y, z \) as integers written in binary. Then \( \text{SUMEQUAL} \in L \).

### 2 Complete languages

Log-space reductions are space-efficient reductions. They are useful when studying completeness for space-bounded computation.

**Definition 2.1** (Log-space reductions). Let \( A, B \) be two languages. We say that \( A \) reduces to \( B \) under log-space reductions, denoted \( A \lessdot_L B \), if there exists a log-space computable function \( f : \{0,1\}^* \to \{0,1\}^* \) such that \( x \in A \iff f(x) \in B \).

**Claim 2.2.** Let \( A, B, C \) be language. Let \( S(n) = \Omega(\log n) \) be a space bound.

1. If \( A \lessdot_L B \) and \( B \lessdot_L C \) then \( A \lessdot_L C \).
2. If \( A \lessdot_L B \) and \( B \in \text{SPACE}(S) \) then \( A \in \text{SPACE}(S) \).
Proof. We only prove the first item, the second is similar. Let \( x \) be an input for \( A \). Let \( f : \{0, 1\}^* \to \{0, 1\}^* \) be the reduction from \( A \) to \( B \) computable in log-space, and let \( g : \{0, 1\}^* \to \{0, 1\}^* \) be the reduction from \( B \) to \( C \) computable in log-space. We need to show that \( g(f(x)) \) is also computable in log-space. Define the languages:

\[
L_1 = \{(x, i) : f(x)_i = 1\}, \quad L_2 = \{(x, i) : g(x)_i = 1\}, \quad L_3 = \{(x, i) : g(f(x))_i = 1\}.
\]

By assumption \( L_1, L_2 \) are in log-space, and we need to show that \( L_3 \) is also in log-space. Let \( M_1 \) be a log-space TM deciding \( L_1 \) and \( M_2 \) be a log-space TM deciding \( L_2 \). Consider the following TM \( M_3 \) which will decide \( L_3 \). Let \( x \) be the input and let \( y = f(x) \). Consider running \( M_2 \) on \((y, i)\), where in addition we keep a counter for the input head location of \( M_2 \). If the input head is at coordinate \( j \) then it needs to read \( y_j \). We compute it “on-the-fly” by computing \( f(x)_j \) using \( M_1 \).

The total space requirements are: \( O(\log n) \) for simulating \( M_2(y) \); \( O(\log n) \) for remembering the input head location of \( M_2 \); \( O(\log n) \) for simulating \( M_1(x) \). So the total space used is \( O(\log n) \), which means that \( M_3 \) is also a log-space machine.

**Definition 2.3** (Complete languages). Let \( C \) be a class of computable languages. A language \( A \) is \( C \)-hard under log-space reductions if for any \( B \in C \) we have \( B <_L A \). If also \( A \in C \) then we say \( A \) is \( C \)-complete under log-space reductions. When \( C \) is a space class (like PSPACE or NL) we would abbreviate that \( A \) is simply \( C \)-complete, where the log-space reductions would be implicit.

We next proceed to give a complete language for various space classes. Note that any language in LOGSPACE is (trivially) also LOGSPACE-complete, so to make it interesting, we should consider richer classes.

### 3 Nondeterministic log-space complete language

The configuration of a deterministic Turing machine of space \( S(n) \) can be described in space \( O(S(n)) \) (tape contents; head locations; state). Hence, we can represent the Turing machine by a graph. Nodes of this graph are all the possible configurations, where the graph will have \( 2^{O(S(n))} \) many vertices. The transition function maps one configuration to the next, hence this is a directed graph with out-degree at most 1. The following is a warm-up.

**Claim 3.1.** The following language is in LOGSPACE:

\[
CONN-DEG1 = \{(G, s, t) : G \text{ directed graph with out-degree } \leq 1, \text{ with a path from } s \text{ to } t\}.
\]

**Proof.** Assume \( G \) is given as an adjacency matrix. We can in log-space scan the input and for a vertex \( v \) find if it has an outgoing edge to another vertex \( u \) or not. Let \( v = s \) be the start vertex. Iteratively move \( v \) to the next vertex until either: \( v = t \) (in which case we accept), \( v \) has no outgoing edge (reject), we made more than \( n \) steps (run into a loop, reject).  

3
Theorem 3.2. The following language is NL-complete:

\[ \text{CONN} = \{(G, s, t) : G \text{ directed graph with a path from } s \text{ to } t\} \]

Proof. Let's show first that CONN ∈ NL. The “proof” is a description of a path from \( s \) to \( t \), which is a sequence of nodes \( p = (v_0, v_1, \ldots, v_m) \). The verifier on input \( G, s, t, p \) does the following:

1. Verify that \( v_0 = s \) and \( v_m = t \).
2. For \( i = 0, \ldots, m - 1 \), verify that the edge \((v_i, v_{i+1})\) is in \( G \).

Note that the verifier can be implemented in log-space, as each verification step can be done in \( O(\log n) \) space, as well as the counter over \( i \).

Next, we show that CONN is NL-hard. Fix a language \( A \in \text{NL} \). Let \( x \) be an input for which we want to check whether \( x \in A \). We will build a function \( f(x) = (G, s, t) \) running in log-space so that \( x \in A \iff f(x) \in \text{CONN} \). Recall that by definition, \( A \in \text{NL} \) means that there exists a NTM \( M \) running in space \( O(\log |x|) \) that computes \( A \). We may assume that when \( M \) accepts an input, its head is in the start position and the work tape is empty, so that there is just one accepting configuration.

Define a graph \( G = G_x \) which describes its configuration graph:

- **Vertices**: The vertices correspond to configurations of \( M \). They include description of the tape head locations, the content of the work tape, and the state. These can be described using \( O(\log |x|) \) bits.

- **Edges**: Given two nodes \( u, v \), there is a direct edge \( u \rightarrow v \) if the NTM \( M \) can reach \( v \) from \( u \) using one of its two transition functions.

Note that \( G \) has out-degree \( \leq 2 \). Let \( s \) be the node corresponding to the initial configuration, \( t \) the accepting configuration. A path in \( G \) from \( s \) to \( t \) corresponds to a computation path of \( M \) that accepts \( x \). Moreover, we can compute the vertices (or specific bits in them) and edges (i.e. adjacency matrix) in log-space, by simulating one step of \( M \). So, the reduction is in log-space.

The connectivity question makes sense also for undirected graphs. Surprisingly, this can be solved in log-space! The algorithm to do so is quite involved, and builds on beautiful math of expander graphs.

Theorem 3.3 (Reingold [2]). The following language is in LOGSPACE:

\[ \text{CONN-UNDIRECTED} = \{(G, s, t) : G \text{ undirected graph with a path from } s \text{ to } t\} \]
4 PSPACE complete language

A quantified boolean formula (QBF) is a formula of the form

\[ \psi = Q_1 x_1 Q_2 x_2 \ldots Q_n x_n \varphi(x_1, \ldots, x_n) \]

where \( Q_i \in \{\exists, \forall\} \) and \( \varphi \) is a CNF formula. This extends SAT or UNSAT, which allow for only one quantifier. Define the language:

\[ TQBF = \{ \text{true QBF formulas} \} \]

**Theorem 4.1.** \( TQBF \) is PSPACE-complete under poly-time reductions (and even under log-space reductions).

**Proof.** We first show \( TQBF \in \text{PSPACE} \). Given a QBF \( \psi = Q_1 x_1 \ldots Q_n x_n \varphi(x_1, \ldots, x_n) \) define

\[ f_i(\psi; a_1, \ldots, a_i) = Q_{i+1} x_{i+1} \ldots Q_n x_n \varphi(a_1, \ldots, a_i, x_{i+1}, \ldots, x_n) \]

This is a “partial assignment” to some of the inputs. We want to compute \( \psi = f_0(\psi) \), we will do so inductively. If \( Q_{i+1} = \exists \) then \( f_i(\psi; a_1, \ldots, a_i) = f_{i+1}(\psi; a_1, \ldots, a_i, 0) \lor f_{i+1}(\psi; a_1, \ldots, a_i, 1) \), and if \( Q_{i+1} = \forall \) then \( f_i(\psi; a_1, \ldots, a_i) = f_{i+1}(\psi; a_1, \ldots, a_i, 0) \land f_{i+1}(\psi; a_1, \ldots, a_i, 1) \). Assume we have a Turing machine \( M_i \) computing \( f_i \) in space \( S_i \). Then \( M_i \) runs \( M_{i+1} \) twice (using the same memory), plus it needs \( O(1) \) overhead memory for bookkeeping. Clearly \( f_n \) is computable in \( P \) and in particular in \( \text{PSPACE} \). Hence \( f_0 \) is computable in \( \text{PSPACE} \).

We next argue that \( TQBF \) is PSPACE-hard. Let \( A \in \text{PSPACE} \). Let \( G \) be the configuration graph of \( A \), where we can think of the input as part of the configuration if we wish. Each vertex of \( G \) is represented by \( m = \text{poly}(n) \) bits. Define

\[ \psi_i(u, v) = \text{there is a path from } u \text{ to } v \text{ of length } \leq 2^i. \]

Let \( s, t \) be the vertices representing the start and end configuration. We would like to compute \( \psi_m(u, v) \). A simple way to do so is by using

\[ \psi_{i+1}(u, v) = \exists w, \psi_i(u, w) \land \psi_i(w, v). \]

However, this will produce a formula of exponential size. To get a formula of polynomial size, we use the trick

\[ \psi_{i+1}(u, v) = \exists w \forall a, b((a = u \land b = w) \lor (a = w \land b = v)) \implies \psi_i(a, b). \]

Clearly we can transfer \( \psi_i \) to \( \psi_{i+1} \) in polynomial time. With some care, we can make this into a CNF. We some more care, this entire operation can actually be done in log-space. \( \Box \)
5 Nondeterministic vs deterministic space

It is conjectured that NL = LOGSPACE. The following theorems provide some partial answers.

**Theorem 5.1** (Savitch [3]). \(NSPACE \subset SPACE(S^2(n))\). In particular, \(NPSPACE = PSPACE\) and \(NL \subset SPACE(\log^2 n)\).

**Proof.** This is a stripped down version of the proof that TQBF \(\in PSPACE\). Let \(A \in NSPACE(S)\). Let \(x \in \{0, 1\}^n\) be a potential input for which we want to decide if \(x \in A\). Let \(G\) be the configuration graph of a Turing machine deciding \(A\) on \(x\). Membership in \(A\) is equivalent to checking if there is a directed path in \(G\) between vertices \(s, t\). Define

\[
\psi_i(u, v) = \text{there is a path between } u \text{ and } v \text{ of length } \leq 2^i.
\]

Then

\[
\psi_{i+1}(u, v) = \exists w, \psi_i(u, w) \land \psi_i(w, v).
\]

In order to compute \(\psi_{i+1}\) we run \(\psi_i\) twice, but since we run it sequentially both applications can use the same space. We need additional space \(S(n)\) to enumerate the value of \(w\). Note that as \(|G| \leq 2^{S(n)}\) then there is a path between \(s, t\) if \(\psi_{S(n)}(s, t) = 1\). This takes \(O(S^2(n))\) space to compute.

Let \(UNCONN = \{(G, s, t) : \text{there is no directed path in } G \text{ from } s \text{ to } t\}\)

We can define coNL (languages which can be refuted in log-space) and get that UNCONN is coNL-complete. It was a surprise when it was proven in the late 80s that NL is closed under complementation, namely that NL=coNL.

**Theorem 5.2** (Immerman [1] and Szelepcsényi [4]). \(UNCONN \in NL\). Hence \(NL = coNL\).

**Proof.** Recall that by definition, a language \(A\) is in nondeterministic log-space if there exists a NTM which computes \(A\) and runs in log-space. For the proof it will be easier to consider an equivalent model: \(A \in NL\) if there exists a TM \(M\) and \(c > 0\) such that

(i) \(x \in A \iff \exists y, |y| \leq |x|^c, M(x, y) = 1\)

(ii) \(M(x, y)\) uses \(O(\log |x|)\) space

(iii) \(y\) is given in a separate tape (witness tape) on which the head can only move to the right. That is, \(y\) is read one symbol at a time, and the head can never return to previously read symbols.

The equivalence proof is basically as follows: \(y\) describes the sequence of choices of which transition function of the NTM to take.

Let \(G\) be a directed graph and \(s, t\) vertices in \(G\). Define

\[
C_i = \{\text{vertices reachable from } s \text{ in at most } i \text{ steps}\}.
\]
We already know that there is a witness that $v \in C_i$ which can be verified in log-space: a list of vertices $v_0, \ldots, v_j$ for $j \leq i$ such that $v_0 = s, v_j = v$ and each two nodes in the path are adjacent. Note that indeed, this witness can be verified in log-space while being read from left to right. The length of this witness is $O(n \log n)$.

We will show that there exist more complicated witnesses, still verifiable in space $O(\log n)$ and in a read-once left-to-right fashion, for:

(a) A witness that $v \notin C_i$, given that we know $|C_i|$.

(b) A witness for $|C_i|$, given that we know $|C_{i-1}|$.

Detailed description:

(a) A witness for $v \notin C_i$ given that we know $|C_i|$ is the following: for each $u \in C_i$, in increasing order, we give the witness that $u \in C_i$. The verifier then verifies that:

- The nodes $u$ are in increasing order;
- The witness for each $u$ is correct;
- The number of $u$ encountered equals $|C_i|$.
- The node $v$ was not one of the nodes $u$ given.

Observe that the verifier needs only log-space, and reads the witness from left to right. The length of the witness is $O(|C_i| \cdot n \log n) = O(n^2 \log n)$.

(b) A witness for $|C_i|$ given $|C_{i-1}|$ is the following: for each vertex $v \in G$ in order,

- Whether $v \in C_i$ or not;
- If $v \in C_i$, a node $w$ such that $(w, v) \in G$ and a witness that $w \in C_{i-1}$.
- If $v \notin C_i$, for every node $w$ such that $(w, v) \in G$, a witness that $w \notin C_{i-1}$.

Observe that the verifier needs only log-space, and reads the witness from left to right. The length of the witness is $O(n^3 \log n)$.

The final proof is a concatenation of all the relevant witnesses. That is: first, a witness that $|C_0| = 1$; then a witness for $|C_1|$ given that we know $|C_0|$, then a witness for $|C_2|$ given that we know $|C_1|$, and so on. At the end, we add a witness that $t \notin C_n$ given that we know $|C_n|$. The total witness length is then $O(n^4 \log n)$, and it can be verified in log-space.
References


