Efficient Algorithms and Intractable Problems

Daniel Deng

1 Complexity Analysis

1.1 Partial Sums

$$S_k = \sum_{n=1}^{k} a_n = \frac{k}{2}(a_1 + a_k) \qquad \text{(Arithmetic Series)}$$

$$S_k = \sum_{n=1}^{k} a_1(r)^n = a_1\left(\frac{1-r^k}{1-r}\right) \qquad \text{(Geometric Series)}$$

1.2 Asymptotic Relations

$$\begin{aligned} f = O(g) &\approx f(n) \leq c \cdot g(n) \\ f = o(g) &\approx f(n) < c \cdot g(n) \\ f = \Omega(g) &\approx f(n) \geq c \cdot g(n) \\ f = \omega(g) &\approx f(n) > c \cdot g(n) \\ f = \Theta(g) &\approx f(n) = c \cdot g(n) \end{aligned}$$

Remark. $O(i^n \mid i > 1) > O(n^j) > O(log^k n)$

Theorem 1.1 (Master Theorem). *If $T(n) = aT([n/b]) + O(n^d)$ for some constants $a > 0$, $b > 1$, and $d \geq 0$, then*

$$T(n) = \begin{cases} \Theta(n^d) & a < b^d \\ \Theta(n^d \log n) & a = b^d \\ \Theta(n^{\log_b a}) & a > b^d \end{cases}$$

2 Polynomial Interpolation

Given a degree n polynomial $A(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n$, the relationship between its values and coefficients can be represented by

$$\begin{bmatrix} A(x_0) \\ A(x_1) \\ \vdots \\ A(x_{n-1}) \end{bmatrix} = \begin{bmatrix} 1 & x_0 & x_0^2 & \cdots & x_0^{n-1} \\ 1 & x_1 & x_1^2 & \cdots & x_1^{n-1} \\ & & \vdots & & \\ 1 & x_{n-1} & x_{n-1}^2 & \cdots & x_{n-1}^{n-1} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{n-1} \end{bmatrix} \qquad \text{(evaluation)}$$

where the matrix M is a *Vandermonde* matrix.

2.1 Fast Fourier Transform (FFT)

Definition 2.1 (Discrete Fourier Transform Matrix)**.** For polynomials of degree $< n$ (n is even; polynomials can be 0-padded), the Discrete Fourier Transform can be represented by the matrix

$$M_n(\omega) = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & \omega & \omega^2 & \cdots & \omega^{n-1} \\ & & \vdots & & \\ 1 & \omega^j & \omega^{2j} & \cdots & \omega^{(n-1)j} \\ & & \vdots & & \\ 1 & \omega^{n-1} & \omega^{2(n-1)} & \cdots & \omega^{(n-1)(n-1)} \end{bmatrix}$$

where $\omega = e^{2\pi i/n}$ is the nth root of unity, and $M_n(\omega)$ is an unitary matrix whose columns forms the *Fourier Basis.*

Remark. $M_n^{-1}(\omega) = \frac{1}{n}\overline{M_n(\omega)} = \frac{1}{n}M_n(\omega^{-1})$

Algorithm 1: Fast Fourier transform

Input: A coefficient vector, $\vec{a} = \langle a_0, \ldots, a_{n-1} \rangle$ and the nth root of unity, ω.
Output: $M_n(\omega)\vec{a}$

Function `FFT(`$\vec{a}$, ω`):`
  if $\omega = 1$ **then**
    return $\vec{a}$
  else
    // $A(x) = A_{even}(x^2) + xA_{odd}(x^2)$
    $\langle A_e(0), \ldots, A_e(n/2-1) \rangle \leftarrow \text{FFT}(\langle a_0, a_2, \ldots, a_{n-2} \rangle, \omega^2)$
    $\langle A_o(0), \ldots, A_o(n/2-1) \rangle \leftarrow \text{FFT}(\langle a_1, a_3, \ldots, a_{n-1} \rangle, \omega^2)$
    for $j := 0$ *to* $n/2 - 1$ **do**
      $A(j) \leftarrow A_e(j) + \omega^j A_o(j)$
      $A(j + n/2) \leftarrow A_e(j) - \omega^j A_o(j)$
  return $\langle A(0), \ldots, A(n-1) \rangle$

Remark. If A is evaluated at points $\pm\omega_0, \ldots, \pm\omega_{n/2-1}$, then $A_e(x^2)$ and $A_o(x^2)$ will only need to evaluate half the amount of points due to squaring.

$$T(n) = 2T(n/2) + O(n) = O(n \log n)$$

2.2 Applications of FFT

Algorithm 2: Fast Polynomial Multiplication

Input: Coefficient vectors, a and b, and the nth root of unity, ω.
Output: The coefficient vector of $A(x)B(x)$

$\hat{\vec{a}} \leftarrow M_n(\omega)\vec{a}$ (FFT)
$\hat{\vec{b}} \leftarrow M_n(\omega)\vec{b}$
for $i = 0$ *to* $n - 1$ **do**
  $\hat{c}_i \leftarrow \hat{a}_i \hat{b}_i$
return $\frac{1}{n} M_n(\omega^{-1})\hat{\vec{c}}$ (inverse matrix)

Definition 2.2 (Cross-Correlation)**.** $corr(\vec{x}, \vec{y})[k] = \sum x_i y_{i-k}$, which measures similarity.

Algorithm 3: Cross-Correlation

Input: Two signal vectors, $\vec{x}$ and $\vec{y}$.
Output: $corr(\vec{x}, \vec{y})$

$X(t) \leftarrow x_{m-1} + x_{m-2}t + \cdots + x_0 t^{m-1}$
$Y(t) \leftarrow y_0 + y_1 t + \cdots + y_{n-1} t^{n-1}$
$Q(t) \leftarrow X(t)Y(t)$ (Fast Polynomial Multiplication)
return $\vec{q}$

3 Graphs

Definition 3.1 (Graph)**.** A graph is a pair $G = (V, E)$, typically represented by an adjacency matrix or an adjacency list.

Table 1: Graph representations.

	Space	Connectivity	getNeighbors(u)	DFS Runtime
Adjacency Matrix	$\Theta(\|V\|^2)$	$O(1)$	$\Theta(\|V\|)$	$\Theta(\|V\|^2)$
Adjacency List	$\Theta(\|V\| + \|E\|)$	$\Theta(degree(u))$	$\Theta(degree(u))$	$\Theta(\|V\| + \|E\|)$

3.1 Depth-First Search

Algorithm 4: Depth-first search

Input: V, E of directed graph G.

```
Function DFS(V, E):
    n ← |V|
    clk ← 1
    visited ← boolean[n]
    preorder, postorder = int[n]
    for v ∈ V do
        if !visited[v] then
            EXPLORE(v)

Function EXPLORE(v):
    visited[v] ← True
    preorder[v] ← clk++
    for (v, w) ∈ E do
        if !visited[w] then
            EXPLORE(w)
    postorder[v] ← clk++
/* Preorder-postorder intervals are either nested or disjoint.     */
/* postorder[u] ≤ postorder[v] iff (u, v) is a back edge.          */
/* G contains a cycle iff it contains a back edge.                 */
```

3.1.1 Applications of DFS

Algorithm 5: Topological sort.

Input: A directed cyclic graph G.
Output: An ordered list of V such that u_i comes before v_i for all $(u_i, v_i) \in E$ (i.e., ordered by decreasing dependency).

```
post ← DFS-visited vertexes ordered by postorder visits
return reverse(post)
```

Definition 3.2 (Strongly Connected Component)**.** A SCC is a maximal partition of a directed graph in which every vertex is reachable from every other vertex.

$$\begin{aligned} u \text{ is in sink SCC of graph } G &\Leftrightarrow u \text{ is in source SCC of reverse graph } G \\ &\Leftrightarrow \text{u is in source SCC if highest postorder number.} \end{aligned}$$

3.2 Single-Source Shortest Path

Algorithm 6: Single-Source Shortest Path

Input: A directed graph G and a start vertex S.
Output: Two arrays $prev[|V|]$ (shortest-path predecessor) and $dist[|V|]$ (shortest-path distance).

```
Function BFS(G, S):
    /* Must have uniform edge weights.  O(|V| + |E|) runtime.          */
Function Dijkstra (G, S):
    /* Must have positive edge weights.  O(|V| log |V| + |E|) runtime if
       implemented using Fibonacci heap.                              */
Function Bellman-Ford (G, S):
    /* Can have aribitrary edge weights.                              */
```

3.3 Minimum Spanning Tree

Algorithm 7: Minimum spanning tree.

Input: A graph G and a starting vertex v.
Output: The minimum spanning tree T of G.

/* Use the cut property. */

Function Prim(G, v)**:**
  /* Sequentially adds the closest neighbor of the running set. $O(|E| + \log |V|)$ runtime if implemented using Fibonacci heap. */

Function Kruskal(G, v)**:**
  /* Sequentially adds the shortest edge that does not create a cycle. $O(|E| \log |V|)$ runtime if implemented using Union-Find data structure. */

4 Greedy Algorithm

Definition 4.1 (Greedy Algorithm)**.** A greedy algorithm is one that builds the solution iteratively using a sequence of local choices.

Algorithm 8: Example greedy algorithms.

Function `SCHEDULING`**:**

`/* Find the maximum set of jobs that can be completed within time by iteratively select the next job to have the smallest end time without conflicting existing schedule.` $O(n \log n)$ `runtime if sorting the collection of jobs first. */`

Function `HUFFMAN`**:**

`/* Find a prefix tree for prefix-free Huffman coding by iteratively combine the two least frequent elements of the alphabet and retrieve the order of the prefix tree accordingly.` $O(n \log n)$ `runtime if implemented with min-heap. */`

Input: A set of partitions $S = \{S_1, \dots, S_m\}$ that covers the universe $\{1, \dots, n\}$.
Output: The indices of the smallest sub-collection of S that covers the universe.

Function `SET-COVER`**:**

`/* Greedy search yields sub-optimal but competitive solution to the set-cover problem. If the optimal solution uses` k `sets, then the greedy solution uses at most` $k \ln n$ `sets. */`

$A \leftarrow \{1, \dots, n\}$
$B \leftarrow \emptyset$
while $|A| > 0$ **do**
  let $i \in [m] \setminus B$ be s.t. $|A \cap S_i|$ is maximum
  $A \leftarrow A \setminus S_i$
  $B \leftarrow B \cup i$
return B

5 Union-Find

Definition 5.1 (Amortized Analysis)**.** Suppose a data structure supports k operations. Then the amortized cost of each operation is t_i if for any sequence of operations with N_i of O_i operations, the total time is at most $\sum_{i=1}^{k} t_i N_i$.

Algorithm 9: Union-find (disjoint forest implementation).

```
/* O((m + n) log* n) runtime.                                    */
parent[1, ..., n]
rank[1, ..., n] // rank is defined as the height if no path compression
    occur.
Function MAKE-SET(x):
    parent[x] ← x
    rank[x] ← 0
Function FIND(x):
    if x = parent[x] then
        return x
    parent[x] ← FIND(parent[x]) // path compression
    return parent[x]
Function UNION(x, y):
    x ← FIND(x)
    y ← FIND(y)
    if x = y then
        return // no work needed
    if rank[x] > rank[y] then
        swap x and y
    parent[x] ← y if rank[x] = rank[y] then
        rank[y] ← rank[y] + 1
```

Remark. Union-Find Invariants:

- a tree rooted at x has $\geq 2^{r[x]}$ items;
- $(\forall x)$, if x is not a root, $r[p[x]] > r[x]$;
- the number of items of exactly rank k is $\leq \frac{n}{2^k}$.

6 Dynamic Programming

Definition 6.1 (Top-Down DP/Memoization)**.** Recursion + look-up table

Definition 6.2 (Bottom-Up DP)**.** Fill up the look-up table iteratively instead of recursively

Remark. Bottom-up DP sometimes have better memory

6.1 Bellman-Ford

Definition 6.3 (Bellman-Ford)**.** An algorithm for finding the SSSP on a directed graph with potentially negative weights. The algorithm defines a function $f(t,k) :=$ the length of the shortest path from s to t using $\leq k$ edges, and wishes to solve for $f(t, n-1)$. The recurrence relation of the algorithm is

$$f(t,k) = \begin{cases} \infty & k = 0, t \neq s \\ 0 & k = 0, t = s \\ \min \begin{cases} f(t, k-1) \\ \min_{(v,t)\in E} w(v,t) + f(v, k-1) \end{cases} & else \end{cases}$$

Remark. Negative cycle detection: $\exists$ negative cycle $\Leftrightarrow \exists v, f(v,n) < f(v, n-1)$

Algorithm 10: Bellman-Ford

Input: G, s.

initialize $T[1,\ldots,n]$ to all ∞

$T[s] \leftarrow 0$

for $k = 1$ *to* $n-1$ **do**

  foreach $(u,v) \in E$ **do**

    $T[v] \leftarrow \min \begin{cases} T[v] \\ w(u,v) + T(u) \end{cases}$

return T

- Memory: $O(n)$ with bottom-up
- Runtime: $O(n^2 + mn)$

6.2 Floyd-Warshall

Definition 6.4 (Floyd-Warshall)**.** An algorithm for finding the all pairs shortest path (APSP) on a directed graph. Assume the graph is complete (pretend $w(e) = \infty$ for all

$e \notin E$), the algorithm defines a function $f(i,j,k) :=$ the length of the shortest path from i to j when all intermediate vertices in the path must be in $\{1,\ldots,k\}$. The recurrence relation is

$$f(i,j,k) = \begin{cases} w(i,j) & k=0, i \neq j \\ 0 & k=0, i=j \\ \min \begin{cases} f(i,j,k-1) \\ f(i,k,k-1) + f(k,j,k-1) \end{cases} & else \end{cases}$$

Algorithm 11: Floyd-Warshall

Input: G

initialize $T[1\ldots n][1\ldots n]$ such that $T[i][j] \leftarrow w(i,j)$ for all i,j

for $k = 1$ *to* n **do**

  for $i = 1$ *to* n **do**

    for $j = 1$ *to* n **do**

      $T[i][j] \leftarrow \begin{cases} T[i][j] \\ T[i][k] + T[k][j] \end{cases}$

return T

- Memory: $O(n^2)$
- Runtime: $O(n^3)$

6.3 Longest Increasing Subsection

Definition 6.5 (LIS)**.** Define $f(last, i) :=$ length of the LIS of $A[i\ldots n]$ such that all values used are $> A[last]$. The recurrence relation is

$$f(last,i) = \begin{cases} 0 & i = n+1 \\ f(last, i+1) & A[i] \leq A[last] \\ \max \begin{cases} f(last, i+1) \\ f(i, i+1) + 1 \end{cases} \end{cases}$$

- Memory: $O(n)$
- Runtime: $O(n^2)$

6.4 Knapsack

Definition 6.6 (Knapsack)**.** Given an array $A[1 \dots n]$ of items, each being a (weight, value) pair. Given a knapsack that can hold $\leq W$ weight, find the maximum value containable in the knapsack. The algorithm for solving this problem defines a function $f(i, C) :=$ maximum value we can pack among $A[i \dots n]$ with capacity C. The recurrence relation is

$$f(i, C) = \begin{cases} 0 & i = n + 1 \\ f(i + 1, C) & w[i] > C \\ \max \begin{cases} f(i + 1, C) \\ f(i + 1, C - w[i]) + v[i] \end{cases} & else \end{cases}$$

- Memory: $O(W)$
- Runtime: $O(nW)$ *pseudopolynomial

Remark. For knapsack problems with replacement, the recurrence relation is instead

$$f(C) = \max_i \left(f(C - w[i]) + v[i] \right)$$

6.5 Traveling Salesman Problem

Definition 6.7 (Traveling Salesman Problem)**.** Given n locations with distances $D[i][j]$. The traveling salesman wishes to visit all locations, starting at 1, while minimizing total travel distance. The DP algorithm defines a function $f(i, S) :=$ minimum traveling distance to visit all locations in S when starting at 1. The recurrence relation is

$$f(i, S) = \begin{cases} 0 & S \neq \emptyset \\ \min_{x \in S} \left(D[i][x] + f\left(x, S \setminus \{x\}\right) \right) & else \end{cases}$$

- Memory: $O(\sqrt{n} \cdot 2^n)$
- Runtime: $O(n^2 \cdot 2^n)$

6.6 Matrix Chain Multiplication

Definition 6.8 (Matrix Chain Multiplication)**.** Given $s_1, \dots, s_{n+1}$ such that A_i is a $s_i \times s_{i+1}$ matrix, and we want to find the minimum number of flops to compute $A_1 \times \cdots \times A_n$. The DP algorithm defines a function $f(i, j) :=$ minimum number of flops to compute $A_i \times \cdots \times A_j$. The recurrence relation is

$$f(i, j) = \begin{cases} 0 & i = j \\ \min_{i \leq k \leq j} \left(f(i, k) + f(k + 1, j) + s_i s_{j+i} s_{k+1} \right) & else \end{cases}$$

- Memory: $O(n^2)$
- Runtime: $O(n^3)$

7 Linear Programming

Definition 7.1 (Linear Programming)**.** Linear programming (LP) describes a broad class of optimization tasks in which both the constraints and the optimization criterion are linear functions. The optimum of a linear program is achieved at a vertex of the convex feasible region.

Remark. A linear program does not have an optimum *iff* its feasible region is infeasible and/or unbounded.

Definition 7.2 (Simplex Method)**.** A standard greedy algorithm for solving LP by hill-climbing on vertices of the feasible region.

Remark. Solves real-life LP in polynomial time.

7.1 LP Conversion

1. (Maximization $\leftrightarrow$ minimization) multiply the coefficients of the objective function by -1
2. (Inequality $\rightarrow$ equality) $ax \leq b \rightarrow ax + s = b \mid s \geq 0$
3. (Equality $\rightarrow$ Inequality) $ax = b \rightarrow ax \leq b \wedge ax \geq b$
4. (Signed $\leftrightarrow$ unsigned) $x \leftrightarrow x^+ - x^- \mid x^+, x^- \geq 0$

7.2 Duality

Theorem 7.1 (Duality theorem)**.** *If a linear program has a bounded optimum, then so does its dual, and the two optimum values coincide (strong duality; weak duality states that primal opt.* $\leq$ *dual opt.).*

Primal LP:

$$\begin{aligned} \max c^{\mathsf{T}} x \\ Ax \leq b \\ b \geq 0 \end{aligned}$$

Dual LP:

$$\begin{aligned} \min y^{\mathrm{T}} b \\ y^{\mathrm{T}} A \geq c^{\mathrm{T}} \\ y \geq 0 \end{aligned}$$

Remark. Dual/Primal unbounded $\implies$ Primal/Dual unfeasible.

7.3 Network Flow

Definition 7.3 (Flow)**.** Given a directed graph $G = (V, E)$ with capacities $c_e > 0$ on all edges. The flow f from source s to sink t satisfies the constraints:

1. For all $e \in E$,
$$0 \leq f_e \leq c_e$$

2. For all $e \in E \setminus \{s, t\}$,
$$\sum_{(w,u)\in E} f_{wu} = \sum_{(u,z)\in E} f_{uz} \quad \text{(conservation of flow)}$$

Remark. By the conservation principle,
$$\text{size}(f) = \sum_{(s,u)\in E} f_{su}$$

Algorithm 12: Ford-Fulkerson

`// Simplex algorithm for solving max-flow problem. Pseudopolynomial time complexity;` $O(|E|F)$

Input: $G = (V, E), s, t$

Output: f

`//` G_f `:= residual graph (also contains back-edges)`

while $\exists$ *an augmenting path in* G_f **do**
- Find an arbitrary augmenting path P from s to t
- Augment flow f along P
- Update G_f

Theorem 7.2 (Max-flow Min-cut Theorem)**.** *The size of the maximum flow in a network equals the capacity of the smallest* (s, t)*-cut* (L, R) *(total capacity of the edges crossing the cut)*

Remark. L contains all reachable vertices from s in the final residual G^f and R contains all remaining vertices.

7.4 Zero-Sum Game

Theorem 7.3 (Min-Max Theorem)**.** *For zero-sum games, there exists an equilibrium such that*
$$\max_x \min_y \sum_{i,j} G_{i,j} x_i y_j = \min_y \max_x \sum_{i,j} G_{i,j} x_i y_j$$

Remark. To convert game strategies to LP:

- $\max\limits_{x} \min\limits_{y} \sum_{i,j} G_{i,j} x_i y_j \implies$

$$\begin{aligned} \max z \\ \forall y, \sum_{i,j} G_{i,j} x_i y_j \geq z \\ \sum_i x_i = 1 \\ \forall i, x_i \geq 0 \end{aligned}$$

- $\min\limits_{y} \max\limits_{x} \sum_{i,j} G_{i,j} x_i y_j \implies$

$$\begin{aligned} \min w \\ \forall x, \sum_{i,j} G_{i,j} x_i y_j \leq w \\ \sum_j y_j = 1 \\ \forall j, y_j \geq 0 \end{aligned}$$

It is apparent that the two LPs are dual; therefore, the equilibrium can be found in polynomial time via LP.

8 Multiplicative Weight Updates

Definition 8.1 (Online Decision Making)**.** A problem where one chooses to follow expert $i^{(t)}$ out of n experts on day $t \in \{1, \dots, T\}$, who incurs a loss of $l_i^{(t)}$ on day t ($\forall i, t, l_i^{(t)}$ is bounded by $[0, 1]$; range can be normalized), with the goal of minimizing the total loss

$$L := \sum_{t=1}^{T} l_i^{(t)}$$

Realistically, the problem aims to minimize the regret

$$R := L - L^* \qquad \left(L^* := \min_{i \in [n]} \sum_{t=1}^{T} l_i^{(t)} \right)$$

Remark. It would be trivial to define the offline optimum L^* as $\sum_{t=1}^{T} \min_{i \in [n]} l_i^{(t)}$ in minimizing regret.

8.1 Hedge/MWU

Algorithm 13: Hedge/MWU

`/* Defined expected loss on day` t `to be` $L_t := \left\langle x^{(t)}, l^{(t)} \right\rangle$ `and the total loss to be` $L := \sum_{t=1}^{T} L_t$`, where` $x^{(t)}$ `is the probability distribution of choosing any expert on day` t`. */`

Input: $\epsilon \in [0, \frac{1}{2}]$.

1. $\forall i \in [n], w_i^{(1)} \leftarrow 1$
2. $x_i^{(t)} \leftarrow \frac{w_i^{(t)}}{W^{(t)}}$ `//` $\left(W^{(t)} := \sum_{j=1}^{n} w_j^{(t)} \right)$
3. $w_i^{(t+1)} \leftarrow w_i^{(t)} (1 - \epsilon)^{l_i^{(t)}}$

Lemma 8.1. $W^{(T+1)} \geq (1 - \epsilon)^{L^*}$

Proof.

$$\begin{aligned} W^{(T+1)} &\geq w_{i^*}^{(T+1)} \\ &= \prod_{t+1}^{T} (1 - \epsilon)^{l_{i^*}^{(t)}} \\ &= (1 - \epsilon)^{L^*} \end{aligned}$$

□

Lemma 8.2. $W^{(T+1)} \leq n \cdot \prod_{t=1}^{T}(1 - \epsilon \cdot L_t)$

Proof. TODO □

Theorem 8.3. *Hedge*(ϵ) *achieves* $\mathbb{E}[R] \leq \epsilon \cdot T + \frac{\ln n}{\epsilon}$ *(or* $\mathbb{E}[R] \leq 2\sqrt{T \ln n}$ *if* $\epsilon = \sqrt{\frac{\ln n}{T}}$*).*

Proof.

$$
\begin{aligned}
&(1-\epsilon)^{L^*} \leq n \cdot \prod_{t=1}^{T}(1 - \epsilon \cdot L_t) \\
\implies &L^* \ln(1-\epsilon) \leq \ln n + \sum_{t+1}^{n} \ln(1 - \epsilon \cdot L_t) \\
\implies &L^*(-\epsilon - \epsilon^2) \leq \ln n - \epsilon \sum_{t=1}^{T} L_t \\
\implies &\sum_{t=1}^{T} L_t - L^* \leq \frac{\ln n}{\epsilon} + \epsilon \cdot L^* \\
\implies &\mathbb{E}[R] \leq \epsilon \cdot T + \frac{\ln n}{\epsilon}
\end{aligned}
$$

□

Remark. $\forall z \in [0, \frac{1}{2}], -z - z^2 \leq \ln(1-z) \leq -z$

9 Reductions

Definition 9.1 (Reduction)**.** Given two problems A and B. If A reduces to B, $\exists$ efficient algorithm for $B \implies \exists$ efficient algorithm for A.

10 Search Problems

Definition 10.1 (Binary relations)**.**

$$(x, w) \in R \subseteq \{0,1\}^* \times \{0,1\}^*$$