Technische Universität Dresden

International Center for Computational Logic

COMPLEXITY THEORY

Lecture 5: Time Complexity and Polynomial Time

Sergei Obiedkov

Knowledge-Based Systems

TU Dresden, 27 Oct 2025

Time Complexity

Measuring Complexity

Complexity Theory

Study the fine structure of decidable languages.

Goal

Classify languages by the amount of resources needed to solve them.

Resources

When dealing with Turing machines, we will primarily consider

- time: the running time of algorithms (steps on a Turing-machine)
- space: the amount of additional memory needed
(cells on the Turing-tapes)

Time and Space Bounded Turing Machines

Definition 5.1: Consider a Turing machine $\mathcal{M}$ and a function $f: \mathbb{N} \to \mathbb{R}^+$.

(1) $\mathcal{M}$ is f-time bounded if it halts on every input $w \in \Sigma^*$ after $\leq f(|w|)$ steps.

(2) $\mathcal{M}$ is f-space bounded if it halts on every input $w \in \Sigma^*$ using $\leq f(|w|)$ cells on its tapes.

(Here we typically assume that Turing machines have a separate input tape that we do not count in measuring space complexity.)

Notation 5.2: Sometimes notations like "$f(n)$-time bounded" are used, assuming inputs to be of length n
$\leadsto$ we use this when convenient, e.g., to write "n^3-bounded"

Big-O and Small-o

Algorithms are often judged by their asymptotic complexity, i.e., their behaviour in the limit.

We recall and extend the definition from Lecture 1:

Definition 5.3: The Big-O notation classifies functions using asymptotic upper bounds ($f, g\colon \mathbb{N} \to \mathbb{R}^+$):

$$f(n) = O(g(n)) \quad \text{iff} \quad \exists c > 0\ \exists n_0 \in \mathbb{N}\ \forall n > n_0 : f(n) \leq c \cdot g(n)$$

Then f is asymptotically bounded by g up to a constant factor.

Big-O and Small-o

Algorithms are often judged by their asymptotic complexity, i.e., their behaviour in the limit.

We recall and extend the definition from Lecture 1:

Definition 5.3: The Big-O notation classifies functions using asymptotic upper bounds ($f, g\colon \mathbb{N} \to \mathbb{R}^+$):

$$f(n) = O(g(n)) \quad \text{iff} \quad \exists c > 0\ \exists n_0 \in \mathbb{N}\ \forall n > n_0 \colon f(n) \leq c \cdot g(n)$$

Then f is asymptotically bounded by g up to a constant factor.

Definition 5.4: The small-o notation classifies functions by functions that dominate them:

$$f(n) = o(g(n)) \quad \text{iff} \quad \forall c > 0\ \exists n_0 \in \mathbb{N}\ \forall n > n_0 \colon f(n) \leq c \cdot g(n)$$

Then f is asymptotically dominated by g.

Relatives of the O Notation

There are a number of further asymptotic notations besides Big-O and small-o. Their essence and underlying intuition is as follows:

Notation	$C = \lim_{n\to\infty} \frac{f(n)}{g(n)}$	Intuition
$f \in O(g)$	$C < \infty$	"$f \leq g$"
$f \in \Omega(g)$	$C > 0$	"$f \geq g$"
$f \in \Theta(g)$	$0 < C < \infty$	"$f = g$"
$f \in o(g)$	$C = 0$	"$f < g$"
$f \in \omega(g)$	$C = \infty$	"$f > g$"

Note: Both "$f \in O(g)$" and "$f = O(g)$" etc. are sometimes used in the literature, with the same intended meaning.

Relaxed Time and Space Bounds

We can use Big-O notation to generalise bounded TMs:

Definition 5.5: A Turing machine $\mathcal{M}$ is

(1) $O(g(n))$-time bounded if it is f-time bounded for some f with $f(n) = O(g(n))$

(2) $O(g(n))$-space bounded if it is f-space bounded for some f with $f(n) = O(g(n))$

Deterministic Complexity Classes

Bounding TMs is the basis for both complexity theory and for studies of algorithmic complexity.

Definition 5.6: Let $f : \mathbb{N} \to \mathbb{R}^+$ be a function.

(1) $\mathrm{DTime}(f(n))$ is the class of all languages **L** for which there is an $O(f(n))$-time bounded deterministic Turing machine deciding **L**.

(2) $\mathrm{DSpace}(f(n))$ is the class of all languages **L** for which there is an $O(f(n))$-space bounded deterministic Turing machine deciding **L**.

Notation 5.7: Sometimes $\mathrm{Time}(f(n))$ is used instead of $\mathrm{DTime}(f(n))$.

Is Complexity Theory Impossible in Practice?

The classes DTIME(f) and DSPACE(f) depend on

- details of the computational model
- details of the input encoding
- details of the implementation

An exact specification of such bounds is often extremely hard.

Is Complexity Theory Impossible in Practice?

The classes DTIME(f) and DSPACE(f) depend on

- details of the computational model
- details of the input encoding
- details of the implementation

An exact specification of such bounds is often extremely hard.

Example 5.8: A naive algorithm can perform matrix multiplication in $O(n^3)$ time, assuming that arithmetic operations take constant time each.

Is Complexity Theory Impossible in Practice?

The classes DTIME(f) and DSPACE(f) depend on

- details of the computational model
- details of the input encoding
- details of the implementation

An exact specification of such bounds is often extremely hard.

Example 5.8: A naive algorithm can perform matrix multiplication in $O(n^3)$ time, assuming that arithmetic operations take constant time each. Since many decades, researchers have been searching for better solutions: $O(n^{2.808})$ [Strassen, 1969], $O(n^{2.796})$ [Pan, 1978], $O(n^{2.780})$ [Bini et al., 1979], $O(n^{2.522})$ [Schönhage, 1981], $O(n^{2.517})$ [Romani, 1982], $O(n^{2.496})$ [Coppersmith & Winograd, 1981], $O(n^{2.479})$ [Strassen, 1986], $O(n^{2.376})$ [Coppersmith & Winograd, 1990], $O(n^{2.374})$ [Stothers, 2010], $O(n^{2.373})$ [Williams, 2011], $O(n^{2.37286})$ [Alman & Williams, 2020], $O(n^{2.371866})$ [Duan, Wu, & Zhou, 2022], and $O(n^{2.371552})$ [Williams, Xu, Xu, & Zhou, 2024]

Is Complexity Theory Impossible in Practice?

The classes DTIME(f) and DSPACE(f) depend on

- details of the computational model
- details of the input encoding
- details of the implementation

An exact specification of such bounds is often extremely hard.

Example 5.8: A naive algorithm can perform matrix multiplication in $O(n^3)$ time, assuming that arithmetic operations take constant time each. Since many decades, researchers have been searching for better solutions: $O(n^{2.808})$ [Strassen, 1969], $O(n^{2.796})$ [Pan, 1978], $O(n^{2.780})$ [Bini et al., 1979], $O(n^{2.522})$ [Schönhage, 1981], $O(n^{2.517})$ [Romani, 1982], $O(n^{2.496})$ [Coppersmith & Winograd, 1981], $O(n^{2.479})$ [Strassen, 1986], $O(n^{2.376})$ [Coppersmith & Winograd, 1990], $O(n^{2.374})$ [Stothers, 2010], $O(n^{2.373})$ [Williams, 2011], $O(n^{2.37286})$ [Alman & Williams, 2020], $O(n^{2.371866})$ [Duan, Wu, & Zhou, 2022], and $O(n^{2.371552})$ [Williams, Xu, Xu, & Zhou, 2024]

Conjectured optimal solution: $O(n^{2+o(1)})$.

Defining Complexity Classes

Solution: Make complexity classes big enough to hide such details.

$$\mathsf{P} = \mathsf{PTime} = \bigcup_{d \geq 1} \mathsf{DTime}(n^d)$$ polynomial time

$$\mathsf{Exp} = \mathsf{ExpTime} = \bigcup_{d \geq 1} \mathsf{DTime}(2^{n^d})$$ exponential time

$$\mathsf{2Exp} = \mathsf{2ExpTime} = \bigcup_{d \geq 1} \mathsf{DTime}(2^{2^{n^d}})$$ double-exponential time

$$\mathsf{E} = \mathsf{ETime} = \bigcup_{d \geq 1} \mathsf{DTime}(2^{dn})$$ exp. time with linear exponent

$$\mathsf{L} = \mathsf{LogSpace} = \mathsf{DSpace}(\log n)$$ logarithmic space

$$\mathsf{PSpace} = \bigcup_{d \geq 1} \mathsf{DSpace}(n^d)$$ polynomial space

$$\mathsf{ExpSpace} = \bigcup_{d \geq 1} \mathsf{DSpace}(2^{n^d})$$ exponential space

Time Complexity Classes

$$\mathsf{P} = \mathsf{PTime} = \bigcup_{d\geq 1} \mathsf{DTime}(n^d) \qquad \text{polynomial time}$$

$$\mathsf{Exp} = \mathsf{ExpTime} = \bigcup_{d\geq 1} \mathsf{DTime}(2^{n^d}) \qquad \text{exponential time}$$

$$\mathsf{2Exp} = \mathsf{2ExpTime} = \bigcup_{d\geq 1} \mathsf{DTime}(2^{2^{n^d}}) \qquad \text{double-exponential time}$$

Note: Complexity classes are classes of languages.

Observation: The following relationships are clear from the definition:

$$\mathsf{P} \subseteq \mathsf{ExpTime} \subseteq \mathsf{2ExpTime} \subseteq \mathsf{3ExpTime} \subseteq \mathsf{4ExpTime} \subseteq \ldots$$

A Hierarchy of Complexity Classes?

Many fundamental questions arise:

- Can we always solve more problems if we have more resources?

A Hierarchy of Complexity Classes?

Many fundamental questions arise:

- Can we always solve more problems if we have more resources?
- If not, how much more resources do we need to be able to solve strictly more problems?

A Hierarchy of Complexity Classes?

Many fundamental questions arise:

- Can we always solve more problems if we have more resources?
- If not, how much more resources do we need to be able to solve strictly more problems?
- How do the complexity classes relate to each other?

A Hierarchy of Complexity Classes?

Many fundamental questions arise:

- Can we always solve more problems if we have more resources?
- If not, how much more resources do we need to be able to solve strictly more problems?
- How do the complexity classes relate to each other?
- Are there any tools by which we can show that a problem is in any of these classes but not in another?

$\leadsto$ discussed in future lectures

A Hierarchy of Complexity Classes?

Many fundamental questions arise:

- Can we always solve more problems if we have more resources?
- If not, how much more resources do we need to be able to solve strictly more problems?
- How do the complexity classes relate to each other?
- Are there any tools by which we can show that a problem is in any of these classes but not in another?

$\leadsto$ discussed in future lectures

- How do we classify “efficient” in terms of complexity classes?

$\leadsto$ coming up next

Different Definitions of Complexity Classes?

How is complexity affected by the chosen model of computation?

- Is DTime(f) the same for multi-tape TMs?
- And how about non-deterministic TMs?
- Or TMs with a two-way infinite tape?
- Or random access machines?
- …

Different Definitions of Complexity Classes?

How is complexity affected by the chosen model of computation?

- Is DTime(f) the same for multi-tape TMs?
- And how about non-deterministic TMs?
- Or TMs with a two-way infinite tape?
- Or random access machines?
- ...

Many complexity classes are robust against many such variations

$\leadsto$ coming up next

Polynomial Time

Polynomial Time

An “intuitive” definition of “efficient”:

- Any linear time computation is “efficient”.
- Any program that
  - performs “efficient” operations (e.g. linear number of iterations) and
  - only uses “efficient” subprograms

  is “efficient”.

Polynomial Time

An "intuitive" definition of "efficient":

- Any linear time computation is "efficient".
- Any program that
  - performs "efficient" operations (e.g. linear number of iterations) and
  - only uses "efficient" subprograms

  is "efficient".

This turns out to be equivalent to PTime.

$$\text{PTime} := \bigcup_{d \geq 1} \text{DTime}(n^d)$$

PTime serves as a mathematical model of "efficient" computation.

Robustness of the Definition

If PTime is to be the mathematical model of efficient computation,
it should not depend on

- the exact computational model we are using,
- or how we encode the input (within reason).

Multi-Tape Turing Machines

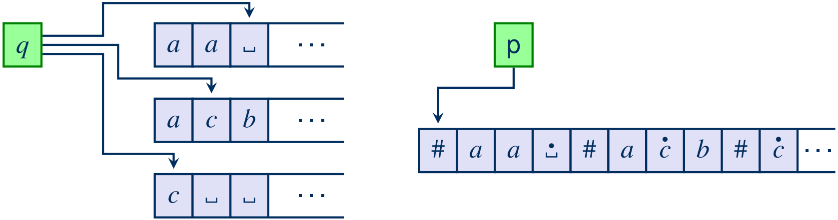
Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof: Simulate a multi-tape TM with a single-tape TM as shown in Lecture 2:



Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps
- Then it updates the whole tape in one pass: $O(f(n))$ steps

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps
- Then it updates the whole tape in one pass: $O(f(n))$ steps
- Sometimes the whole tape is shifted to make space: at most k times $O(f(n))$ steps

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps
- Then it updates the whole tape in one pass: $O(f(n))$ steps
- Sometimes the whole tape is shifted to make space: at most k times $O(f(n))$ steps
- Overall: one step is simulated in $O(f(n))$ steps

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps
- Then it updates the whole tape in one pass: $O(f(n))$ steps
- Sometimes the whole tape is shifted to make space: at most k times $O(f(n))$ steps
- Overall: one step is simulated in $O(f(n))$ steps
- Simulating $f(n)$ such steps takes $f(n) \cdot O(f(n)) = O(f^2(n))$ steps

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps
- Then it updates the whole tape in one pass: $O(f(n))$ steps
- Sometimes the whole tape is shifted to make space: at most k times $O(f(n))$ steps
- Overall: one step is simulated in $O(f(n))$ steps
- Simulating $f(n)$ such steps takes $f(n) \cdot O(f(n)) = O(f^2(n))$ steps
- Tape initialisation takes $O(n)$ steps (irrelevant)

Multi-Tape Turing Machines

Theorem 5.9 (Sipser, Theorem 7.8): Consider a function f with $f(n) \geq n$. Then, for every $f(n)$-time bounded k-tape Turing machine ($k > 1$), there is an equivalent $O(f^2(n))$-time bounded single-tape Turing machine.

Proof (cont.): Then analyse how long this simulation really takes:

- Observation: the tapes can never have more than $f(n)$ symbols on them
- The simulation scans the whole tape once to find out what to do: $O(f(n))$ steps
- Then it updates the whole tape in one pass: $O(f(n))$ steps
- Sometimes the whole tape is shifted to make space: at most k times $O(f(n))$ steps
- Overall: one step is simulated in $O(f(n))$ steps
- Simulating $f(n)$ such steps takes $f(n) \cdot O(f(n)) = O(f^2(n))$ steps
- Tape initialisation takes $O(n)$ steps (irrelevant)

The entire simulation is possible in $O(f^2(n))$ time. □

P is Robust for Multi-Tape TMs

Let $\mathsf{DTime}_k(f(n))$ denote "$\mathsf{DTime}(f(n))$ for a k-tape TM".

Theorem 5.10:

$$\bigcup_{d\in\mathbb{N}} \mathsf{DTime}(n^d) = \bigcup_{d\in\mathbb{N}} \mathsf{DTime}_k(n^d) \text{ for every } k \geq 1$$

Proof: The inclusion $\subseteq$ is clear.
The inclusion $\supseteq$ follows from the previous Theorem 5.9. $\square$

Robustness Against Other Models of Computation

P is robust against further models of computation:

(1) We can simulate $f(n)$ steps of a two-way infinite k-tape Turing-machine with an equivalent standard k-tape TM in $O(f(n))$ steps.

(2) We can simulate $f(n)$ steps of a RAM with a 7-tape TM in $O(f^3(n))$ steps. Vice-versa in $O(f(n))$ steps.

Robustness Against Other Models of Computation

P is robust against further models of computation:

(1) We can simulate $f(n)$ steps of a two-way infinite k-tape Turing-machine with an equivalent standard k-tape TM in $O(f(n))$ steps.

(2) We can simulate $f(n)$ steps of a RAM with a 7-tape TM in $O(f^3(n))$ steps. Vice-versa in $O(f(n))$ steps.

Consequences:

- PTime is the same for all these models (unlike linear time)
- The exponential time complexity classes are as robust as P

How about non-deterministic TMs?

Robustness Against Other Models of Computation

P is robust against further models of computation:

(1) We can simulate $f(n)$ steps of a two-way infinite k-tape Turing-machine with an equivalent standard k-tape TM in $O(f(n))$ steps.

(2) We can simulate $f(n)$ steps of a RAM with a 7-tape TM in $O(f^3(n))$ steps. Vice-versa in $O(f(n))$ steps.

Consequences:

- PTime is the same for all these models (unlike linear time)
- The exponential time complexity classes are as robust as P

How about non-deterministic TMs?

It is unknown if PTime is robust against this, but most think it is not

$\leadsto$ see next lectures

Linear Speed-Up

The Big-O notation in DTime hides arbitrary constant factors.
Is it justified to rely on this for defining P?

Linear Speed-Up

The Big-O notation in DTime hides arbitrary constant factors.
Is it justified to rely on this for defining P?

Yes, it turns out that we can make multi-tape TMs "arbitrarily fast":

Theorem 5.11 (Linear Speed-Up Theorem): Consider an $f(n)$-time bounded k-tape Turing machine $\mathcal{M} = (Q, \Sigma, \Gamma, \delta, q_0, q_{\text{accept}}, q_{\text{reject}})$ with $k > 1$.

Then, for every constant $c > 0$, there is a $(\frac{1}{c} \cdot f(n) + O(n))$-time bounded k-tape TM $\mathcal{M}' = (Q', \Sigma, \Gamma', \delta', q'_0, q'_{\text{accept}}, q'_{\text{reject}})$ that accepts the same language.

Linear Speed-Up (Proof)

Proof (sketch): Let $\Gamma' := \Sigma \cup \Gamma^m$ where $m := \lceil 6c \rceil$. We construct $\mathcal{M}'$ as follows:

Linear Speed-Up (Proof)

Proof (sketch): Let $\Gamma' := \Sigma \cup \Gamma^m$ where $m := \lceil 6c \rceil$. We construct $\mathcal{M}'$ as follows:

Step 1: Compress $\mathcal{M}$'s input.

Copy the input to tape 2, compressing m symbols into one (i.e., each symbol corresponds to an m-tuple from Γ^m). This takes $O(n)$ steps.

Linear Speed-Up (Proof)

Proof (sketch): Let $\Gamma' := \Sigma \cup \Gamma^m$ where $m := \lceil 6c \rceil$. We construct $\mathcal{M}'$ as follows:

Step 1: Compress $\mathcal{M}$'s input.

Copy the input to tape 2, compressing m symbols into one (i.e., each symbol corresponds to an m-tuple from Γ^m). This takes $O(n)$ steps.

Step 2: Simulate $\mathcal{M}$'s computation, m steps at once.

(1) Read (in 4 steps) symbols to the left, right and the current position and "store" in Q', using $|Q \times \{1, \ldots, m\}^k \times \Gamma^{3mk}|$ extra states.

(2) Simulate (in 2 steps) the next m steps of $\mathcal{M}$ (as $\mathcal{M}$ can only modify the current position and one of its neighbours)

(3) $\mathcal{M}'$ accepts (rejects) if $\mathcal{M}$ accepts (rejects)

For further details see Papadimitriou, Theorem 2.2. $\square$

Different Encodings

Some simple observations:

(1) For any $n \in \mathbb{N}$, the length of the encoding of n in base b_1 and base b_2 are related by a constant factor, for all $b_1, b_2 \geq 2$.

Different Encodings

Some simple observations:

(1) For any $n \in \mathbb{N}$, the length of the encoding of n in base b_1 and base b_2 are related by a constant factor, for all $b_1, b_2 \geq 2$.

(2) For any graph G, the length of its encoding as an

- adjacency matrix
- list of nodes + list of edges
- adjacency list
- …

are all polynomially related.

Different Encodings

Some simple observations:

(1) For any $n \in \mathbb{N}$, the length of the encoding of n in base b_1 and base b_2 are related by a constant factor, for all $b_1, b_2 \geq 2$.

(2) For any graph G, the length of its encoding as an

- adjacency matrix
- list of nodes + list of edges
- adjacency list
- ...

are all polynomially related.

Consequence:

PTime is the same for all these encodings (unlike linear time).

PTime = tractable?

The class Ptime is a reasonable mathematical model of the class of problems which are tractable or solvable in practice.

PTime = tractable?

The class Ptime is a reasonable mathematical model of the class of problems which are tractable or solvable in practice.

However: This correspondence is not exact.

- When the degree of polynomials is very high, the time grows so quickly that in practice the problem is not solvable.
- The constants may also be very large

PTime = tractable?

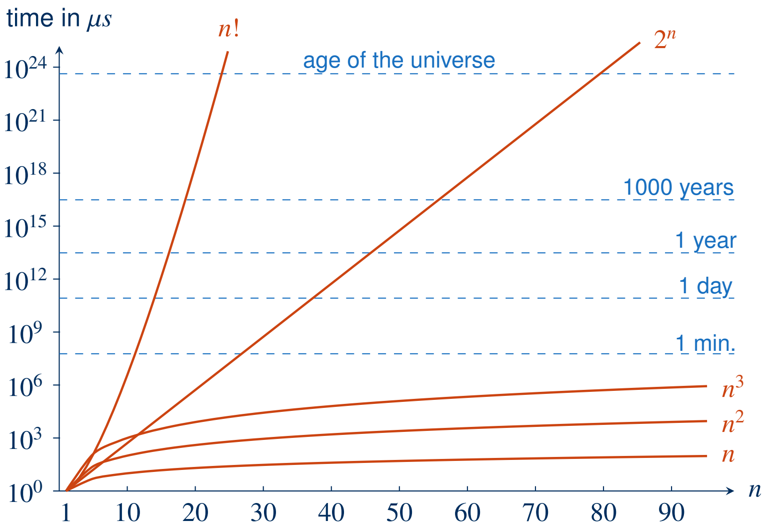
The class Ptime is a reasonable mathematical model of the class of problems which are tractable or solvable in practice.

However: This correspondence is not exact.

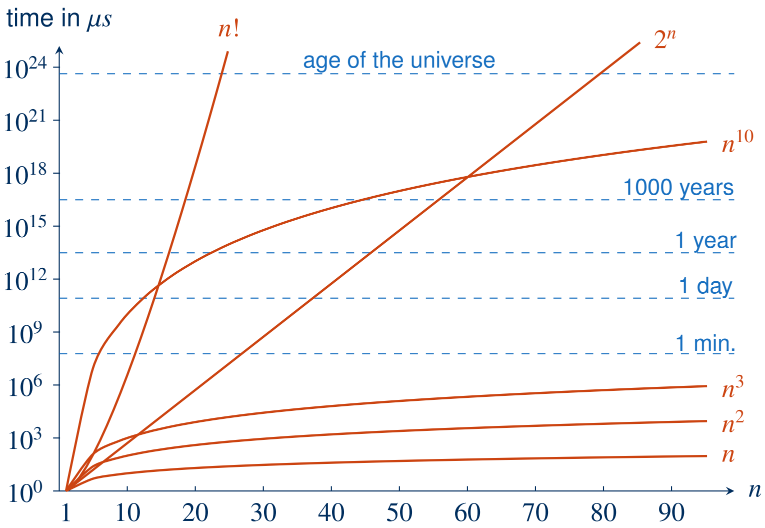
- When the degree of polynomials is very high, the time grows so quickly that in practice the problem is not solvable.
- The constants may also be very large

And yet: For many concrete PTime-problems arising in practice, algorithms with moderate exponents and constants have been found.

Growth Rate of Some Functions



Growth Rate of Some Functions



Problems in P

Proving a Problem is in PTime

- The most direct way to show that a problem is in PTime is to exhibit a polynomial time algorithm that solves it.
- Even a naive polynomial-time algorithm often provides a good insight into how the problem can be solved efficiently.
- Because of robustness, we do not generally need to specify all the details of the machine model or the encoding.

  $\leadsto$ pseudo-code is sufficient

Example: Satisfiability

Some of the most important problems concern logical formulae

Definition 5.12 (Propositional Logic Syntax): Formulae of propositional logic are built up inductively

- (Propositional) Variables: $X_i \qquad i \in \mathbb{N}$
- Boolean connectives: If φ, ψ are propositional formulae then so are
  - $(\psi \vee \varphi)$
  - $(\psi \wedge \varphi)$
  - $\neg\varphi$

Example: Satisfiability

Some of the most important problems concern logical formulae

Definition 5.12 (Propositional Logic Syntax): Formulae of propositional logic are built up inductively

- (Propositional) Variables: $X_i \qquad i \in \mathbb{N}$
- Boolean connectives: If φ, ψ are propositional formulae then so are
  - $(\psi \vee \varphi)$
  - $(\psi \wedge \varphi)$
  - $\neg\varphi$

Example 5.13: The following is a propositional logic formula:

$$(X_1 \vee X_2 \vee \neg X_5) \;\wedge\; (\neg X_2 \vee \neg X_4 \vee \neg X_5) \;\wedge\; (X_2 \vee X_3 \vee X_4)$$

Conjunctive Normal Form

Definition 5.14 (Conjunctive Normal Form): A propositional logic formula φ is in conjunctive normal form (CNF) if

$$\varphi = C_1 \wedge \cdots \wedge C_m$$

where each C_i is a clause, that is, a disjunction of literals

$$C_i = (L_{i1} \vee \cdots \vee L_{ik})$$

and a literal is a variable X_i or a negation $\neg X_i$ thereof.

A CNF φ is in k-CNF is it has at most k literals per clause.

Conjunctive Normal Form

Definition 5.14 (Conjunctive Normal Form): A propositional logic formula φ is in conjunctive normal form (CNF) if

$$\varphi = C_1 \wedge \cdots \wedge C_m$$

where each C_i is a clause, that is, a disjunction of literals

$$C_i = (L_{i1} \vee \cdots \vee L_{ik})$$

and a literal is a variable X_i or a negation $\neg X_i$ thereof.

A CNF φ is in k-CNF is it has at most k literals per clause.

Example 5.15: The following formula is in 3-CNF:

$$(X_1 \vee X_2 \vee \neg X_5) \ \wedge \ (\neg X_2 \vee \neg X_4 \vee \neg X_5) \ \wedge \ (X_2 \vee X_3 \vee X_4)$$

Definition 5.16: A formula φ is satisfiable if it is satisfied by an assignment that maps each variable in φ to either 0 or 1 (and recursively defined for larger fomulae as usual).

Specifically: A formula in CNF is satisfiable if there is an assignment β for variables of φ so that every clause contains at least

- one variable to which β assigns 1, or
- one negated variable to which β assigns 0.

Propositional Logic Semantics

Definition 5.16: A formula φ is satisfiable if it is satisfied by an assignment that maps each variable in φ to either 0 or 1 (and recursively defined for larger fomulae as usual).

Specifically: A formula in CNF is satisfiable if there is an assignment β for variables of φ so that every clause contains at least

- one variable to which β assigns 1, or
- one negated variable to which β assigns 0.

Example 5.17: The formula

$$(X_1 \vee X_2 \vee \neg X_5) \;\wedge\; (\neg X_2 \vee \neg X_4 \vee \neg X_5) \;\wedge\; (X_2 \vee X_3 \vee X_4)$$

is satisfied by $\{X_1 \mapsto 1,\ X_2 \mapsto 0,\ X_3 \mapsto 1,\ X_4 \mapsto 0,\ X_5 \mapsto 1\}$.

The Satisfiability Problem

Related to propositional formulae, the following two problems are the most important:

SAT

Input:	Propositional formula φ in CNF
Problem:	Is φ satisfiable?

***k*-SAT**

Input:	Propositional formula φ in k-CNF
Problem:	Is φ satisfiable?

2-Sat is Polynomial

Theorem 5.18: 2-Sat $\in$ PTime.

2-Sat is Polynomial

Theorem 5.18: 2-Sat $\in$ PTime.

Proof: The following algorithm solves the problem in polynomial time.

Main: Input Γ in CNF

```
bcp(Γ)
if conflict return UNSAT
while Γ ≠ ∅ do
    choose var. X from Γ
    set Γ' := Γ
    assign(Γ, X, 1)
    bcp(Γ)
    if conflict
        Γ := Γ'
        assign(Γ, X, 0)
        bcp(Γ)
        if conflict
            return UNSAT
return SAT
```

bcp(Γ) (boolean constraint propagation)

```
while Γ contains unit-clause C do
    if C = {X}      assign(Γ, X, 1)
    if C = {¬X}     assign(Γ, X, 0)
if Γ contains empty clause return conflict
```

assign(Γ, X, c)

```
if c = 1
    remove from Γ all clauses C with X ∈ C
    remove ¬X from all remaining clauses
if c = 0
    remove from Γ all clauses C with ¬X ∈ C
    remove X from all remaining clauses
```

□

Polynomial-Time Reductions

As for decidability we can use reductions to show membership in PTime.

Definition 5.19: A language $\mathbf{L_1} \subseteq \Sigma^*$ is polynomially many-one reducible to $\mathbf{L_2} \subseteq \Sigma^*$, denoted $\mathbf{L_1} \leq_p \mathbf{L_2}$, if there is a polynomial-time computable function f such that for all $w \in \Sigma^*$

$$w \in \mathbf{L_1} \quad \text{if and only if} \quad f(w) \in \mathbf{L_2}.$$

Polynomial-Time Reductions

As for decidability we can use reductions to show membership in PTime.

Definition 5.19: A language $\mathbf{L_1} \subseteq \Sigma^*$ is polynomially many-one reducible to $\mathbf{L_2} \subseteq \Sigma^*$, denoted $\mathbf{L_1} \leq_p \mathbf{L_2}$, if there is a polynomial-time computable function f such that for all $w \in \Sigma^*$

$$w \in \mathbf{L_1} \qquad \text{if and only if} \qquad f(w) \in \mathbf{L_2}.$$

Theorem 5.20: If $\mathbf{L_1} \leq_p \mathbf{L_2}$ and $\mathbf{L_2} \in$ PTime then $\mathbf{L_1} \in$ PTime.

Proof: The sum and composition of polynomials is a polynomial. $\square$

Summary and Outlook

Complexity classes are based on asymptotic resource estimates, further generalised by considering general classes of bounds (e.g., all polynomial functions)

Ignoring constant factors is justified due to Linear Speedup

P is the most common approximation of “efficient”

Polynomial many-one reductions are used to show membership in P

What’s next?

- NP
- Hardness and completeness
- More examples of problems