Lecture 4: Fixed-Parameter Intractability

(A Short Introduction to Parameterized Complexity)

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Course overview

Monday, June 16 10.30 – 12.30	Tuesday, June 17 10.30 – 12.30	Wednesday, June 18	Thursday, June 19 10.30 – 12.30	Friday, June 20
Algorithmic Techniques			*Formal-Method* & *Algorithmic Techniques*	
Introduction & basic FPT results	**Notions of bounded graph width**		**Algorithmic Meta-Theorems**	
motivation for FPT kernelization, Crown Lemma, Sunflower Lemma	path-, tree-, clique width, FPT-results by dynamic programming, transferring FPT results betw. width		1st-order logic, monadic 2nd-order logic, FPT-results by Courcelle's Theorems for tree and clique-width	(Fair Division)
				14.30 – 16.30
				FPT-Intractability Classes & Hierarchies
			(Fair Division)	motivation for FP-intractability results, FPT-reductions, class XP (slicewise polynomial), W- and A-Hierarchies, placing problems on these hierarchies

Overview

- Motivation for fixed-parameter intractability
- Fixed parameter reductions
- The classes para-NP and XP
- The class W[P]
- Logic preliminaries (continued)
- W-hierarchy
  - definitions
    - with Boolean circuits
    - as parameterized weighted Fagin definability problems
- A-hierarchy
  - definition as parameterized model-checking problems
- picture overview of these classes

Two classical problems

QUERIES
Instance: a relational database D, a conjunctive query α.
Compute: answer to query α from database D.

- QUERIES $\in$ NP-complete.

LTL-MODEL-CHECKING
Instance: a Kripke structure (state space) $\mathcal{K}$, an LTL formula φ
Parameter: size $|\varphi|$ of formula φ
Question: Does $\mathcal{K} \models \varphi$ hold?

- LTL-MODEL-CHECKING $\in$ PSPACE-complete.

Comparing their parameterizations

QUERIES
Instance: a relational database D, a conjunctive query α.
Parameter: size $k = |\alpha|$ of query α
Compute: answer to query α from database D.

- QUERIES $\in$ NP-complete.
- QUERIES $\in O(n^k)$ for $n = \|D\|$, which does not give an FPT result.

LTL-MODEL-CHECKING
Instance: a Kripke structure (state space) $\mathcal{K}$, an LTL formula φ
Parameter: size $k = |\varphi|$ of formula φ
Question: Does $\mathcal{K} \vDash \varphi$ hold?

- LTL-MODEL-CHECKING $\in$ PSPACE-complete,
- LTL-MODEL-CHECKING $\in O(k \cdot 2^{2k} \cdot n) \in$ FPT for $n = \|\mathcal{K}\|$.

Fixed-parameter intractability

'The purpose [. . .] is to give evidence that certain problems are not fixed-parameter tractable (just as the main purpose of the theory of NP*-completeness is to give evidence that certain problems are not polynomial time computable.)*

In classical theory, the notion of NP*-completeness is central to a nice, simple, and far-reaching theory for intractable problems.*

Unfortunately, the world of parameterized intractability is more complex: There is a big variety of seemingly different classes of intractable parameterized problems.'

(Flum, Grohe [2])

Fixed-Parameter tractable

Definition

A parameterized problem $\langle Q, \Sigma, \kappa \rangle$ is *fixed-parameter tractable* (is in FPT) if:

$$\exists f : \mathbb{N} \to \mathbb{N} \text{ computable } \exists p \in \mathbb{N}[X] \text{ polynomial}$$
$$\exists \mathbb{A} \text{ algorithm, takes inputs in } \Sigma^*$$
$$\forall x \in \Sigma^* \Big[\mathbb{A} \text{ decides whether } x \in Q \text{ holds in time } \leq f(\kappa(x)) \cdot p(|x|) \Big]$$

Slices of parameterized problems

The *ℓ-th slice*, for $\ell \in \mathbb{N}$, of a parameterized problem $\langle Q, \kappa \rangle$ is:

$$\langle Q, \kappa \rangle_\ell := \{ x \in Q \mid \kappa(x) = \ell \} \ .$$

Proposition (slices of FPT problems are in PTIME)

Let $\langle Q, \kappa \rangle$ be a parameterized problem, and $\ell \in \mathbb{N}$.
If $\langle Q, \kappa \rangle \in$ FPT, then $\langle Q, \kappa \rangle_\ell \in$ PTIME.

Proof

Let ℓ be fixed. Then for all $x \in \Sigma^*$:
Decide $x \in Q$, $\kappa(x) = \ell$ in time $\le f(\kappa(x)) \cdot p(|x|) = f(\ell) \cdot p(|x|) \in$ PTIME.

A problem not in FPT

The *ℓ-th slice*, for $\ell \in \mathbb{N}$, of a parameterized problem $\langle Q, \kappa \rangle$ is:

$$\langle Q, \kappa \rangle_\ell := \{ x \in Q \mid \kappa(x) = \ell \} \ .$$

Slices of FPT problems are in PTIME

If $\langle Q, \kappa \rangle \in$ FPT, then $\langle Q, \kappa \rangle_\ell \in$ PTIME.

p-COLORABILITY
Instance: A graph $\mathcal{G}$, and $\ell \in \mathbb{N}$.
Parameter: ℓ.
Problem: Decide whether $\mathcal{G}$ is ℓ-colorable.

Consequence: p-COLORABILITY $\notin$ FPT (unless P = NP).

It is well-known: 3-COLORABILITY $\in$ NP-complete. Now since 3-COLORABILITY is the third slice of p-COLORABILITY, the proposition entails p-COLORABILITY $\notin$ FPT unless P = NP.

Polynomial reductions / hardness / completeness

Definition

Let $\langle Q_1, \Sigma_1 \rangle$, $\langle Q_2, \Sigma_2 \rangle$ be classical problems.
An *polynomial-time reduction* from $\langle Q_1, \Sigma_1 \rangle$ to $\langle Q_2, \Sigma_2 \rangle$ is a mapping $R : \Sigma_1^* \to \Sigma_2^*$:

R1. $(x \in Q_1 \iff R(x) \in Q_2)$ for all $x \in \Sigma_1^*$.

R2. R is computable by a polynomial-time algorithm: there is a polynomial $p(X)$ such that R is computable in time $p(|x|)$.

$\langle Q_1, \Sigma_1 \rangle \leq_{\text{pol}} \langle Q_2, \Sigma_2 \rangle$:=
there is a polynomial-time reduction from $\langle Q_1, \Sigma_1 \rangle$ to $\langle Q_2, \Sigma_2 \rangle$.

Proposition

If $\langle Q_1, \Sigma_1 \rangle \leq_{\text{pol}} \langle Q_2, \Sigma_2 \rangle$, then:

$$\langle Q_1, \Sigma_1 \rangle \in \mathrm{P} \iff \langle Q_2, \Sigma_2 \rangle \in \mathrm{P}.$$

$$\langle Q_1, \Sigma_1 \rangle \notin \mathrm{P} \implies \langle Q_2, \Sigma_2 \rangle \notin \mathrm{P}.$$

Let C be class of classical problems.

- $\langle Q, \Sigma \rangle$ is C-hard: if, for all $\langle Q', \Sigma' \rangle \in$ C, $\langle Q', \Sigma' \rangle \leq_{\text{pol}} \langle Q, \Sigma \rangle$.
- $\langle Q, \Sigma \rangle$ is C-complete: if $\langle Q, \Sigma \rangle$ is C-hard, and $\langle Q, \Sigma \rangle \in$ C.

Fixed-parameter tractable reductions

Definition

Let $\langle Q_1, \Sigma_1, \kappa \rangle$, $\langle Q_2, \Sigma_2, \kappa_2 \rangle$ be parameterized problems.
An *fpt-reduction* from $\langle Q_1, \kappa_1 \rangle$ to $\langle Q_2, \kappa_2 \rangle$ is a mapping $R : \Sigma_1^* \to (\Sigma_2)^*$:

R1. $(x \in Q_1 \iff R(x) \in Q_2)$ for all $x \in \Sigma_1^*$.

R2. R is computable by a fpt-algorithm (with respect to κ): there are f computable and $p(X)$ polynomial such that R is computable in time $f(\kappa_1(x)) \cdot p(|x|)$.

R3. $\kappa_2(R(x)) \leq g(\kappa_1(x))$ for all $x \in \Sigma_1^*$, for some computable function $g : \mathbb{N} \to \mathbb{N}$.

$\langle Q_1, \kappa_1 \rangle \leq_{\text{fpt}} \langle Q_2, \kappa_2 \rangle :=$ there is an fpt-red. from $\langle Q_1, \kappa_1 \rangle$ to $\langle Q_2, \kappa_2 \rangle$.

Proposition

If $\langle Q_1, \kappa_1 \rangle \leq_{\text{fpt}} \langle Q_2, \kappa_2 \rangle$, then:

$$\langle Q_1, \kappa_1 \rangle \in \text{FPT} \Longleftarrow \langle Q_2, \kappa_2 \rangle \in \text{FPT}.$$
$$\langle Q_1, \kappa_1 \rangle \notin \text{FPT} \Longrightarrow \langle Q_2, \kappa_2 \rangle \notin \text{FPT}.$$

Comparing parameterizations (revisited)

Definition (computably bounded below)

Let $\kappa_1, \kappa_2 : \Sigma^* \to \mathbb{N}$ parameterizations.

- $\kappa_1 \succeq \kappa_2 \;:\Longleftrightarrow\; \exists g : \mathbb{N} \to \mathbb{N}$ computable $\forall x \in \Sigma^* \big[\, g(\kappa_1(x)) \geq \kappa_2(x) \,\big]$.
- $\kappa_1 \approx \kappa_2 \;:\Longleftrightarrow\; \kappa_1 \succeq \kappa_2 \;\wedge\; \kappa_2 \succeq \kappa_1$.
- $\kappa_1 \succ \kappa_2 \;:\Longleftrightarrow\; \kappa_1 \succeq \kappa_2 \;\wedge\; \neg(\kappa_2 \succeq \kappa_1)$.

Proposition

For all parameterized problems $\langle Q, \kappa_1 \rangle$ and $\langle Q, \kappa_2 \rangle$ with $\kappa_1 \succeq \kappa_2$:

$$\langle Q, \kappa_1 \rangle \in \mathrm{FPT} \;\Longleftarrow\; \langle Q, \kappa_2 \rangle \in \mathrm{FPT}\,,$$
$$\langle Q, \kappa_1 \rangle \notin \mathrm{FPT} \;\Longrightarrow\; \langle Q, \kappa_2 \rangle \notin \mathrm{FPT}\,.$$

Proposition

For all parameterized problems $\langle Q, \kappa_1 \rangle$ and $\langle Q, \kappa_2 \rangle$ with $Q \subseteq \Sigma^*$:

$$\kappa_1 \succeq \kappa_2 \;\Longleftrightarrow\; \langle Q, \kappa_1 \rangle \leq_{\mathrm{fpt}} \langle Q, \kappa_2 \rangle \text{ via } R : \Sigma^* \to \Sigma^*, x \mapsto x.$$

Fixed-parameter tractable reductions

Examples

- p-CLIQUE $\equiv_{\text{fpt}}$ p-INDEPENDENT-SET.
- p-DOMINATING-SET $\equiv_{\text{fpt}}$ p-HITTING-SET.

Non-Example

- For graphs $\mathcal{G} = \langle V, E \rangle$, and sets $X \subseteq V$:

  $$X \text{ is independent set of } \mathcal{G} \iff V \setminus X \text{ is a vertex cover of } \mathcal{G}$$

  yields a polynomial reduction between p-INDEPENDENT-SET and p-VERTEX-COVER, but does not yield an fpt-reduction.

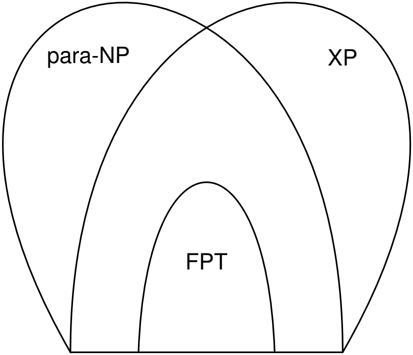
Fpt-reduction closure / hardness / reducibility

Let C be a class of parameterized problems.

We define for all parameterized problems $\langle Q, \kappa \rangle$:

- $\big[\langle Q, \kappa \rangle\big]^{\text{fpt}} := \big\{\langle Q', \kappa' \rangle \mid \langle Q', \kappa' \rangle \leq_{\text{fpt}} \langle Q, \kappa \rangle\big\}$.
- $\big[\mathrm{C}\big]^{\text{fpt}} := \bigcup_{\langle Q, \kappa \rangle \in \mathrm{C}} \big[\langle Q, \kappa \rangle\big]^{\text{fpt}}$
  is the *closure of* C *under fpt-reductions.*
- $\langle Q, \kappa \rangle$ is C*-hard under fpt-reductions*
  if every problem in C is fpt-reducible to $\langle Q, \kappa \rangle$
  that is: $\mathrm{C} \subseteq \big[\langle Q, \kappa \rangle\big]^{\text{fpt}}$, and hence $\big[\mathrm{C}\big]^{\text{fpt}} \subseteq \big[\langle Q, \kappa \rangle\big]^{\text{fpt}}$.
- $\langle Q, \kappa \rangle$ is C*-complete under fpt-reductions*
  if $\langle Q, \kappa \rangle \in \mathrm{C}$ and $\langle Q, \kappa \rangle$ is C-hard under fpt-reductions,
  and then: $\big[\mathrm{C}\big]^{\text{fpt}} = \big[\langle Q, \kappa \rangle\big]^{\text{fpt}}$.

para-NP and XP



para-NP

Definition

A parameterized problem $\langle Q, \Sigma, \kappa \rangle$ is in para-NP if there is a computable function $f : \mathbb{N} \to \mathbb{N}$, and a polynomial $p \in \mathbb{N}[X]$ such that there is a non-deterministic algorithm $\mathbb{A}$ such that:

- $\mathbb{A}$ decides, for all $x \in \Sigma^*$, whether $x \in Q$ in $\leq f(\kappa(x)) \cdot p(|x|)$ steps.

- para-NP is closed under fpt-reductions.
- NP $\subseteq$ para-NP.

Example

- p-CLIQUE, p-INDEPENDENT-SET, p-DOMINATING-SET, p-HITTING-SET, p-COLORABILITY $\in$ para-NP.

- FPT = para-NP if and only if PTIME = NP.
- A non-trivial problem $\langle Q, \kappa \rangle$ is para-NP-complete for fpt-reductions if and only if the union of finitely many slices of $\langle Q, \kappa \rangle$ is NP-complete. Hence a non-trivial problem with at least one NP-complete slice is para-NP-complete.
  - p-COLORABILITY $\in$ para-NP-complete.

XP (slicewise polynomial problems)

Recall: slices of FPT-problems are in PTIME. This suggests a class:

$\mathrm{XP}_{\mathrm{nu}}$, *non-uniform* XP : the class of parameterized problems $\langle Q, \kappa \rangle$, whose slices $\langle Q, \kappa \rangle_k$ are all in PTIME.

- But: $\mathrm{XP}_{\mathrm{nu}}$ contains undecidable problems:
  - Let $Q \subseteq \{1\}^*$ be an undecidable set. Let $\kappa : \{1\}^* \to \mathbb{N}$, $x \mapsto \kappa(x) := \max\{1, |x|\}$. Then $\langle Q, \kappa \rangle \in \mathrm{XP}_{\mathrm{nu}}$.

Definition

A parameterized problem $\langle Q, \Sigma, \kappa \rangle$ is in XP if there is a computable function $f : \mathbb{N} \to \mathbb{N}$ such that there is an algorithm $\mathbb{A}$ such that:

- $\mathbb{A}$ decides $x \in Q$, for all $x \in \Sigma^*$, in $\le f(\kappa(x)) \cdot |x|^{f(\kappa(x))}$ steps;

equivalently, if in addition to computable $f : \mathbb{N} \to \mathbb{N}$ there are polynomials $p_k \in \mathbb{N}[X]$ for all $k \in \mathbb{N}$ such that:

- $\mathbb{A}$ decides $x \in Q$, for all $x \in \Sigma^*$, in $\le f(\kappa(x)) \cdot p_{\kappa(x)}(|x|)$ steps.

XP (slicewise polynomial problems)

Recall: slices of FPT-problems are in PTIME. This suggests a class:

XP_{nu}, *non-uniform* XP : the class of parameterized problems $\langle Q, \kappa \rangle$, whose slices $\langle Q, \kappa \rangle_k$ are all in PTIME.

- But: XP_{nu} contains undecidable problems:
  - Let $Q \subseteq \{1\}^*$ be an undecidable set. Let $\kappa : \{1\}^* \to \mathbb{N}$, $x \mapsto \kappa(x) := \max\{1, |x|\}$. Then $\langle Q, \kappa \rangle \in \text{XP}_{\text{nu}}$.

Definition

A parameterized problem $\langle Q, \Sigma, \kappa \rangle$ is in XP if there is a computable function $f : \mathbb{N} \to \mathbb{N}$ such that there is an algorithm $\mathbb{A}$ such that:

- $\mathbb{A}$ decides $x \in Q$, for all $x \in \Sigma^*$, in $\leq f(\kappa(x)) + |x|^{f(\kappa(x))}$ steps;

equivalently, if in addition to computable $f : \mathbb{N} \to \mathbb{N}$ there are polynomials $p_k \in \mathbb{N}[X]$ for all $k \in \mathbb{N}$ such that:

- $\mathbb{A}$ decides $x \in Q$, for all $x \in \Sigma^*$, in $\leq f(\kappa(x)) \cdot p_{\kappa(x)}(|x|)$ steps.

XP (slicewise polynomial problems)

Example

- p-CLIQUE, p-INDEPENDENT-SET, p-DOMINATING-SET, p-HITTING-SET $\in$ XP.
- p-COLORABILITY $\notin$ XP, because 3-COLORABILITY $\in$ NP-complete.

Proposition

If PTIME $\neq$ NP, then para-NP $\nsubseteq$ XP.

Proof.

If para-NP $\subseteq$ XP, then p-COLORABILITY $\in$ XP. But then it follows that 3-COLORABILITY $\in$ PTIME, and as 3-COLORABILITY is NP-complete, that PTIME $=$ NP. □

Proposition

FPT $\subsetneq$ XP .

Model checking

The *model checking problem* for a class Φ of first-order formulas:

MC(Φ)
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Problem: Decide whether $\mathcal{A} \vDash \varphi$ (that is, $\varphi(\mathcal{A}) \neq \varnothing$).

Theorem

MC(FO) *can be solved in time* $O(|\varphi| \cdot |A|^w \cdot w)$*, where* w *is the width of the input formula* φ *(max. no. of free variables in a subformula of* φ*).*

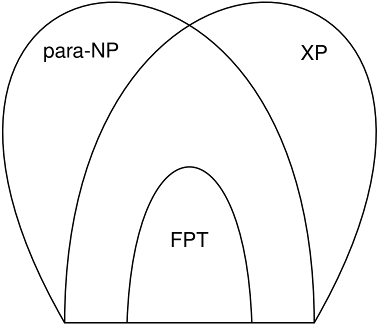
The *parameterized model checking problem* for a class Φ of formulas:

p-MC(Φ).
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Parameter: $|\varphi|$.
Problem: Decide whether $\mathcal{A} \vDash \varphi$.

Theorem

p-MC(Φ) $\in$ XP.

FPT versus para-NP and XP



Proposition

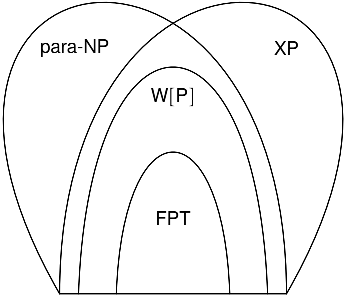
- $\mathrm{FPT} \subseteq \text{para-NP}$, and:
  $\mathrm{FPT} = \text{para-NP}$ if and only if $\mathrm{PTIME} = \mathrm{NP}$.
- $\text{para-NP} \nsubseteq \mathrm{XP}$ if $\mathrm{PTIME} \neq \mathrm{NP}$.
- $\mathrm{FPT} \subsetneqq \mathrm{XP}$.

W[P]

'There is no definite single class that can be viewed as "the parameterized NP". Rather, there is a whole hierarchy of classes playing this role.

The class W[P] can be placed on top of this hierarchy. It is one of the most important parameterized complexity classes.'

(Flum, Grohe [2])



W[P] and limited non-determinism

$\langle Q, \Sigma \rangle \in \mathsf{NP}[f]$ means:

$\iff \exists p(X)$ polynomial $\exists \mathbb{M}$ non-deterministic Turingmachine
$\big(\forall x \in \Sigma^* \big((x \in Q \iff \mathbb{M}$ accepts $x)$
$\wedge$ on input x, $\mathbb{M}$ halts in $\leq p(|x|)$ steps, of which
at most $\leq f(|x|)$ are non-deterministic$\big)$

$\mathsf{NP}[\mathcal{F}] := \bigcup_{f \in \mathcal{F}} \mathsf{NP}[f]$ for class of functions $\mathcal{F}$.

Fact

$$\mathsf{NP}[\log n] = \mathsf{P}\,, \qquad \mathsf{NP}[n^{O(1)}] = \mathsf{NP}\,.$$

W[P]

Definition

- Let Σ be an alphabet, and $\kappa : \Sigma^* \to \mathbb{N}$ a parameterization.

  A nondeterministic Turing machine $\mathbb{M}$ with input alphabet Σ is *κ-restricted* if there are computable functions $f, h : \mathbb{N} \to \mathbb{N}$ and a polynomial $p \in \mathbb{N}_0[x]$ such that on every run with input $x \in \Sigma^*$ the machine $\mathbb{M}$ performs

  - at most $f(\kappa(x)) \cdot p(|x|)$ steps,
  - at most $h(\kappa(x)) \cdot \log |x|$ of them being nondeterministic,

- W[P] contains all problems $\langle Q, \kappa \rangle$ that can be decided by a κ-restricted nondeterministic Turing machine.

W[P] (properties)

Theorems

T1. FPT $\subseteq$ W[P] $\subseteq$ XP $\cap$ para-NP

T2. W[P] is closed under fpt-reductions.

T3. p-CLIQUE, p-INDEPENDENT-SET, p-DOMINATING-SET, and p-HITTING-SET are in W[P].

The W-hierarchy – Boolean circuits

A *(Boolean) circuit* is a DAG in which nodes are labeled:

- nodes of in-degree > 1 as *and-node* or as *or-node*,
- nodes of in-degree $= 1$ as *negation nodes*,
- nodes of in-degree $= 0$ as *Boolean constants* 0 or 1, or *input node* (we assume input nodes to be numbered 1,. . . ,n),
- one node of out-degree 0 is labeled as *output node*.

A circuit $\mathcal{C}$ with n input nodes defines a function $\mathcal{C}(\cdot) : \{0,1\}^n \to \{0,1\}$ (a Boolean function) in the natural way.

- If $\mathcal{C}(x) = 1$, for $x \in \{0,1\}^n$, we say that x *satisfies* $\mathcal{C}$.
- The *weight* of a tuple $x = \langle x_1, \ldots, x_n \rangle \in \{0,1\}^*$ is $\sum_{i=1}^n x_i$.

Definition

We say that $\mathcal{C}$ is *k-satisfiable* if $\mathcal{C}$ is satisfied by a tuple of weight k.

W[P] complete problems

p-WSAT(CIRC)
Instance: A circuit $\mathcal{C}$ and $k \in \mathbb{N}$
Parameter: k.
Problem: Decide whether $\mathcal{C}$ is k-satisfiable.

Theorem

p-WSAT(CIRC) *is* W[P]*-complete under fpt-reductions.*

Definition

The depth of the circuit is the max. length of a path from an input node to the output node. Small nodes have indegree at most 2 while large nodes have indegree > 2. The weft of a circuit is the max. number of large nodes on a path from an input node to the output node. We denote by $\text{CIRC}_{t,d}$ the class of circuits with weft $\leq t$ and depth $\leq d$.

Application

p-DOMINATING-SET $\in$ W[P], since it reduces to p-WSAT($\text{CIRC}_{2,3}$).

Limited non-determinism (classically)

$\langle Q, \Sigma \rangle \in \mathsf{NP}[f]$ means:

$\iff \exists p(X)$ polynomial $\exists \mathbb{M}$ non-deterministic Turingmachine

$\Big(\forall x \in \Sigma^* \Big((x \in Q \iff \mathbb{M}$ accepts $x)$

$\wedge$ on input x, $\mathbb{M}$ halts in $\leq p(|x|)$ steps, of which

at most $\leq f(|x|)$ are non-deterministic$\Big)$

$\mathsf{NP}[\mathcal{F}] := \bigcup_{f \in \mathcal{F}} \mathsf{NP}[f]$ for class of functions $\mathcal{F}$.

Fact

$$\mathsf{NP}[\log n] = \mathsf{P}\,, \qquad \mathsf{NP}[n^{O(1)}] = \mathsf{NP}\,.$$

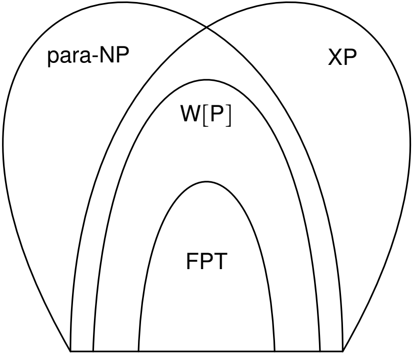
Theorem (Cai, Chen, 1997)

The following are equivalent:

(i) $\mathsf{FPT} = \mathsf{W}[\mathsf{P}]$.

(ii) *There is a computable, nondecreasing, unbounded function* $\iota : \mathbb{N} \to \mathbb{N}$ *such that* $\mathsf{P} = \mathsf{NP}[\iota(n) \cdot \log n]$.

FPT and W[P] versus para-NP and XP



Proposition

$\mathrm{FPT} \subseteq \mathrm{W[P]} \subseteq \mathrm{XP} \cap \text{para-NP}$.

Why is the theory of W[P]/W/A-hardness important?

- Prevents from wasting hours tackling a problem which is fundamentally difficult;
- Finding results on a problem is always a ping-pong game between trying to design a hardness/FPT result;
- There is a hierarchy on parameters and it is worth knowing which is the smallest one such that the problem remains FPT;
- There is a hierarchy on complexity classes and it is worth noting to which extent a problem is hard.

Logic preliminaries (continued)

- *atomic formulas/atoms*: a formula $x = y$ or $Rx_1 \ldots x_n$
- *literal*: an atom or a negated atom
- *quantifier-free formula*: a formula without quantifiers
- formula in *negation-normal form*:
  negations only occur in front of atoms
- formula in *prenex normal form*: formula of the form
  $Q_1 x_1 \ldots Q_k x_k\, \psi$, where ψ is quantifier-free
  and $Q_1, \ldots, Q_k \in \{\exists, \forall\}$
- Σ_0 and Π_0 : the class of quantifier-free formulas
- Σ_{t+1} : class of all formulas $\exists x_1 \ldots \exists x_k \varphi$ where $\varphi \in \Pi_t$
- Π_{t+1} : class of all formulas $\forall x_1 \ldots \forall x_k \varphi$ where $\varphi \in \Sigma_t$

Weighted Fagin definability

Let $\varphi(X)$ be a f-o formula with a free relation variable X with arity s.
Let τ be a vocabulary for φ, plus a relation symbol R of arity s.

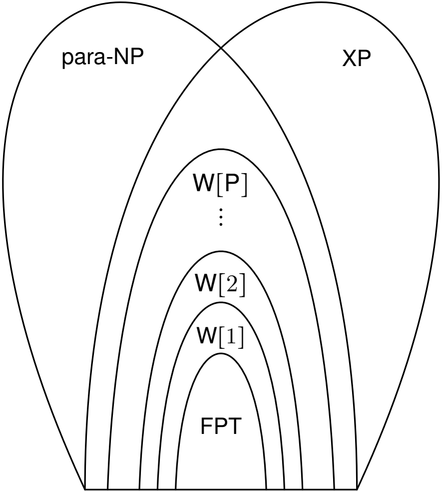
A *solution for φ in a τ-structure $\mathcal{A}$* is a relation $S \subseteq A^s$ such that $\mathcal{A} \models \varphi(\overline{S})$.

The *weighted Fagin definability problem* for $\varphi(X)$ is:

> WD_φ
>
> **Instance:** A structure $\mathcal{A}$ and $k \in \mathbb{N}$.
>
> **Problem:** Decide whether there is a solution $S \subseteq A^s$ for φ of cardinality $|S| = k$.

WD_Φ: the class of all problems WD_φ with $\varphi \in \Phi$, where Φ is a class of first-order formulas with free relation variable X.

W-Hierarchy



W-Hierarchy

p-WD$_\varphi$ (φ a fo-formula with free relation variable X of arity s)
Instance: A structure $\mathcal{A}$ and $k \in \mathbb{N}$.
Parameter: k.
Problem: Is there a relation $S \subseteq A^s$ of cardinality $|S| = k$ with $\mathcal{A} \models \varphi(S)$.

p-WD-Φ: the class of all problems p-WD-φ with $\varphi \in \Phi$, Φ is a class of first-order formulas.

Definition (Downey–Fellows, 1995)

$W[t] := \left[p\text{-WD-}\Pi_t\right]^{\text{fpt}}$, for $t \geq 1$, form the *W-hierarchy*.

Examples

- p-Clique $\in$ W$[1]$.
- p-Dominating-Set $\in$ W$[2]$.
- p-Hitting-Set $\in$ W$[2]$.

W-Hierarchy

p-WD$_\varphi$ (φ a fo-formula with free relation variable X of arity s)
Instance: A structure $\mathcal{A}$ and $k \in \mathbb{N}$.
Parameter: k.
Problem: Is there a relation $S \subseteq A^s$ of cardinality $|S| = k$ with $\mathcal{A} \vDash \varphi(S)$.

p-WD-Φ: the class of all problems p-WD-φ with $\varphi \in \Phi$, Φ is a class of first-order formulas.

Definition (Downey–Fellows, 1995)

$W[t] := \left[p\text{-WD-}\Pi_t\right]^{\text{fpt}}$, for $t \geq 1$, form the *W-hierarchy*.

Examples

- p-CLIQUE $\in$ W$[1]$.
- p-DOMINATING-SET $\in$ W$[2]$.
- p-HITTING-SET $\in$ W$[2]$.

W-Hierarchy

p-WD$_\varphi$ (φ a fo-formula with free relation variable X of arity s)
Instance: A structure $\mathcal{A}$ and $k \in \mathbb{N}$.
Parameter: k.
Problem: Is there a relation $S \subseteq A^s$ of cardinality $|S| = k$ with $\mathcal{A} \models \varphi(S)$.

p-WD-Φ: the class of all problems p-WD-φ with $\varphi \in \Phi$, Φ is a class of first-order formulas.

Definition (Downey–Fellows, 1995)

$W[t] := \left[p\text{-WD-}\Pi_t\right]^{\text{fpt}}$, for $t \geq 1$, form the *W-hierarchy*.

Examples

- p-Clique $\in$ W$[1]$.
- p-Dominating-Set $\in$ W$[2]$.
- p-Hitting-Set $\in$ W$[2]$.

W-hierarchy

Definition

(W-hierarchy) For $t \geq 1$, a parameterized problem $\langle Q, \kappa \rangle$ belongs to the class W$[t]$ if there is a parameterized reduction from $\langle Q, \kappa \rangle$ to p-WSAT(CIRC$_{t,d}$) (with parameter t) for some $d \geq 1$.

FPT $\subseteq$ W$[1]$ $\subseteq$ W$[2]$ $\ldots$

- p-CLIQUE, p-INDEPENDENT-SET are W$[1]$-Complete.
- p-DOMINATING-SET, p-HITTING-SET are W$[2]$-Complete.

Hypothesis: W$[1] \neq$ FPT

Proposition

This definition of the W-hierarchy is equivalent to the one here before. That is, it holds, for all $t \geq 1$:

$$\text{W}[t] = \left[\{p\text{-WSAT}(\text{CIRC}_{t,d}) \mid d \geq 1\}\right]^{\text{fpt}}.$$

W-Hierarchy (properties)

Immediate from definition follows: $\left[p\text{-WD-FO}\right]^{\text{fpt}} = \bigcup_{i=1}^{\infty} \mathrm{W}[i]$.

Theorems

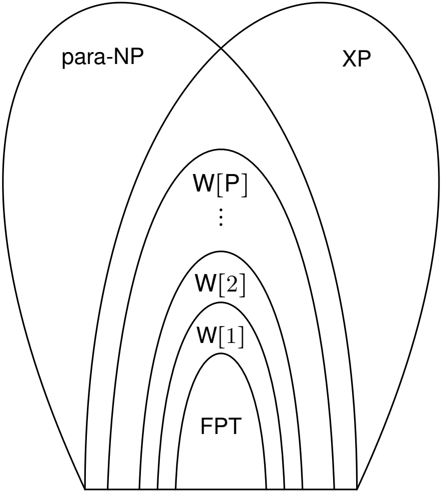
T1. p-WD-FO $\subseteq$ W[P], and hence $\mathrm{W}[t] \subseteq$ W[P] for all $t \geq 1$.

T2. $p\text{-WD-}\Sigma_1 \subseteq$ FPT.

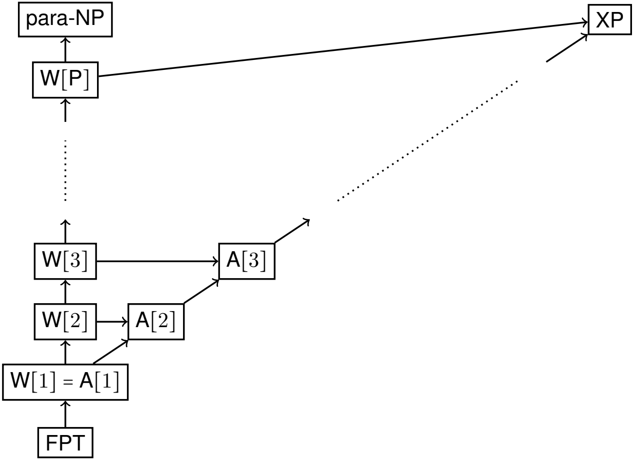
T3. $p\text{-WD-}\Sigma_{t+1} \subseteq p\text{-WD-}\Pi_t$, for all $t \geq 1$.

T4. $\mathrm{W}[t] = \left[p\text{-WD-}\Sigma_{t+1}\right]^{\text{fpt}}$ for all $t \geq 1$.

W-Hierarchy versus para-NP and XP



A-Hierarchy



A-Hierarchy (definition and examples 1,2)

The parameterized model checking problem for a class Φ of formulas:

p-MC(Φ)
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Parameter: $|\varphi|$.
Problem: Decide whether $\varphi(\mathcal{A}) \neq \varnothing$.

Definition (Flum, Grohe, 2001)

$A[t] := \left[p\text{-MC}(\Sigma_t)\right]^{\text{fpt}}$, for $t \geq 1$, form the *A-hierarchy*.

Examples

- p-CLIQUE $\in$ A$[1]$.
- p-DOMINATING-SET $\in$ A$[2]$.

A-Hierarchy (definition and examples 3,4)

The parameterized model checking problem for a class Φ of formulas:

p-MC(Φ)
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Parameter: $|\varphi|$.
Problem: Decide whether $\varphi(\mathcal{A}) \neq \varnothing$.

Definition (Flum, Grohe, 2001)

$A[t] := \left[p\text{-MC}(\Sigma_t)\right]^{\text{fpt}}$, for $t \geq 1$, form the *A-hierarchy*.

Examples

- p-HITTING-SET $\in$ A$[2]$.
- p-SUBGRAPH-ISOMORPHISM $\in$ A$[1]$.

A-Hierarchy (example 5)

The parameterized model checking problem for a class Φ of formulas:

p-MC(Φ)
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Parameter: $|\varphi|$.
Problem: Decide whether $\varphi(\mathcal{A}) \neq \varnothing$.

Definition (Flum, Grohe, 2001)

$A[t] := \left[p\text{-MC}(\Sigma_t)\right]^{\text{fpt}}$, for $t \geq 1$, form the *A-hierarchy*.

Examples

- p-SUBGRAPH-ISOMORPHISM $\in$ A$[1]$.

p-SUBGRAPH-ISOMORPHISM
Instance: Graphs $\mathcal{G}$ and $\mathcal{H}$.
Parameter: The number of vertices of $\mathcal{H}$.
Problem: Does $\mathcal{G}$ have a subgraph isomorphic to $\mathcal{H}$.

A-Hierarchy (example 6)

The parameterized model checking problem for a class Φ of formulas:

p-MC(Φ)
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Parameter: $|\varphi|$.
Problem: Decide whether $\varphi(\mathcal{A}) \neq \varnothing$.

Definition (Flum, Grohe, 2001)

$A[t] := \left[p\text{-MC}(\Sigma_t)\right]^{\text{fpt}}$, for $t \geq 1$, form the *A-hierarchy*.

Examples

- p-VERTEX-DELETION $\in$ A$[2]$.

p-VERTEX-DELETION
Instance: Graphs $\mathcal{G}$ and $\mathcal{H}$, and $k \in \mathbb{N}$.
Parameter: $k + \ell$, where ℓ the number of vertices of $\mathcal{H}$.
Problem: Is it possible to delete at most k vertices from $\mathcal{G}$ such that the resulting graph has no subgraph isomorphic to $\mathcal{H}$?

A-Hierarchy (example 7)

The parameterized model checking problem for a class Φ of formulas:

p-MC(Φ)
Instance: A structure $\mathcal{A}$ and a formula $\varphi \in \Phi$.
Parameter: $|\varphi|$.
Problem: Decide whether $\varphi(\mathcal{A}) \neq \varnothing$.

Definition (Flum, Grohe, 2001)

$A[t] := \left[p\text{-MC}(\Sigma_t)\right]^{\text{fpt}}$, for $t \geq 1$, form the *A-hierarchy*.

Examples

- p-Clique-Dominating-Set $\in$ A$[2]$.

p-Clique-Dominating-Set
Instance: Graphs $\mathcal{G}$, and $k, \ell \in \mathbb{N}$.
Parameter: $k + \ell$, where ℓ the number of vertices of $\mathcal{H}$.
Problem: Decide whether $\mathcal{G}$ contains a set of k vertices from $\mathcal{G}$ that dominates every clique of ℓ elements.

A-Hierarchy (properties)

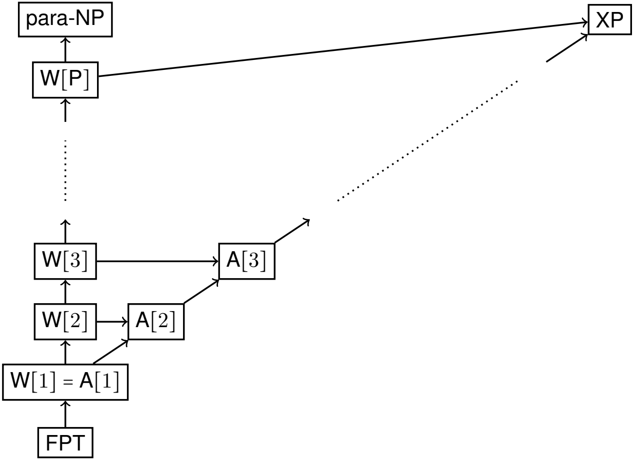
Theorems

T1. $\mathsf{A}[1] \subseteq \mathsf{W}[\mathsf{P}]$.

T2. $\mathsf{W}[t] \subseteq \mathsf{A}[t]$, for all $t \in \mathbb{N}$.

- Unlikely: $\mathsf{A}[t] \subseteq \mathsf{W}[t]$, for $t > 1$.
  Reason:
  - the A-hierarchy are parameterizations of problems that are complete for the levels of the polynomial hierarchy
  - the W-hierarchy is a refinement of NP in parameterized complexity
- Unlikely: $\left[p\text{-MC(FO)}\right]^{\text{fpt}} = \bigcup_{i=1}^{\infty} \mathsf{A}[i]$,
  contrasting with: $\left[p\text{-WD-FO}\right]^{\text{fpt}} = \bigcup_{i=1}^{\infty} \mathsf{W}[i]$.

W-Hierarchy and A-Hierarchy versus para-NP and XP



Revisiting the two problems at start today

QUERIES
Instance: a relational database D, a conjunctive query α.
Parameter: size $k = |\alpha|$ of query α
Compute: answer to query α from database D.

- QUERIES $\in$ NP-complete.
- QUERIES $\in O(n^k)$ for $n = \|D\|$, which does not give an FPT result.
- QUERIES $\in$ W[1] (= strong evidence for it likely not to be in FPT).

LTL-MODEL-CHECKING
Instance: a Kripke structure (state space) $\mathcal{K}$, an LTL formula φ
Parameter: size $k = |\varphi|$ of formula φ
Question: Does $\mathcal{K} \models \varphi$ hold?

- LTL-MODEL-CHECKING $\in$ PSPACE-complete,
- LTL-MODEL-CHECKING $\in O(k \cdot 2^{2^k} \cdot n) \in$ FPT for $n = \|\mathcal{K}\|$.

Summary

- Motivation for fixed-parameter intractability
- Fixed parameter reductions
- The classes para-NP and XP
- The class W[P]
- Logic preliminaries (continued)
- W-hierarchy
  - definitions
    - with Boolean circuits
    - as parameterized weighted Fagin definability problems
- A-hierarchy
  - definition as parameterized model-checking problems
- picture overview of these classes

Course overview

Monday, June 16 10.30 – 12.30	Tuesday, June 17 10.30 – 12.30	Wednesday, June 18	Thursday, June 19 10.30 – 12.30	Friday, June 20
Algorithmic Techniques			*Formal-Method* & *Algorithmic Techniques*	
Introduction & basic FPT results	**Notions of bounded graph width**		**Algorithmic Meta-Theorems**	
motivation for FPT kernelization, Crown Lemma, Sunflower Lemma	path-, tree-, clique width, FPT-results by dynamic programming, transferring FPT results betw. width		1st-order logic, monadic 2nd-order logic, FPT-results by Courcelle's Theorems for tree and clique-width	(Fair Division)
				14.30 – 16.30
				FPT-Intractability Classes & Hierarchies
			(Fair Division)	motivation for FP-intractability results, FPT-reductions, class XP (slicewise polynomial), W- and A-Hierarchies, placing problems on these hierarchies

Example suggestions

Examples

1. FPT results transfer backwards over fpt-reductions:
   If $\langle Q_1, \kappa_1 \rangle \leq_{\text{fpt}} \langle Q_2, \kappa_2 \rangle$, then $Q_2 \in$ FPT implies $Q_1 \in$ FPT.
2. Find the idea for:
   p-DOMINATING-SET $\equiv_{\text{fpt}}$ p-HITTING-SET.
3.

References

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