Automatic Synthesis of Systems with Data

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Monday, September 6th, 2021

Synthesis

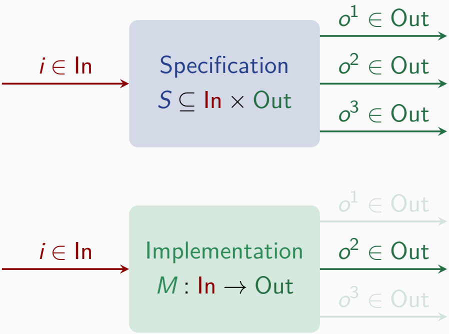
$? \parallel \text{Environment} \models \text{Specification}$

➔ Generate a system from a specification

Implementing a specification

Inputs In

Outputs Out



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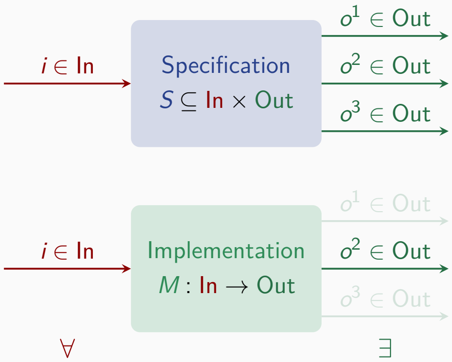


Synthesis

Inputs In

Outputs Out

$\mathcal{S}$ class of specifications $S \subseteq \mathsf{In} \times \mathsf{Out}$

$\mathcal{I}$ class of implementations $M : \mathsf{In} \to \mathsf{Out}$

M fulfils S, written $M \models S$, if for all $i \in \mathsf{In}$, $(i, M(i)) \in S$

Synthesis Problem for $\mathcal{S}$ and $\mathcal{I}$

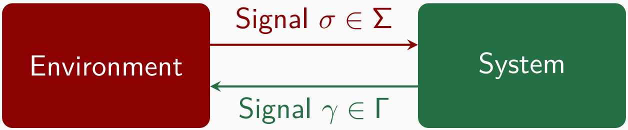
Input: $S \in \mathcal{S}$

Output:
- $M \in \mathcal{I}$ s. t. $M \models S$ if it exists
- **No** otherwise

Reactive Synthesis

$\mathsf{In} = \Sigma^\omega$ $\mathsf{Out} = \Gamma^\omega$

Reactive systems



Interaction $\rightsquigarrow$ $\sigma_1\gamma_1\sigma_2\gamma_2\sigma_3\gamma_3\ldots$

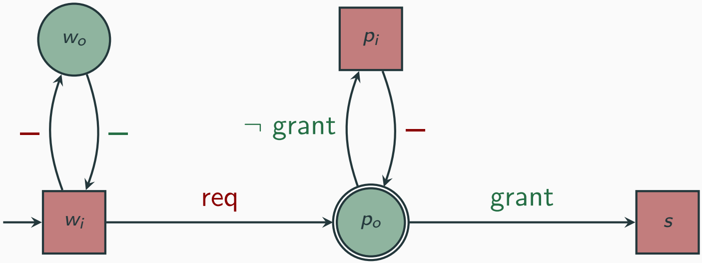
Specification $S \subseteq (\Sigma \cdot \Gamma)^\omega$ in a high-level formalism (MSO, LTL)

Implementation = finite-state machine = reactive system

Running Example

- Server and clients
- Everytime a client makes a request, it must eventually be granted
  ➔ $G(\text{req} \Rightarrow F(\text{grt}))$

ω-Automata

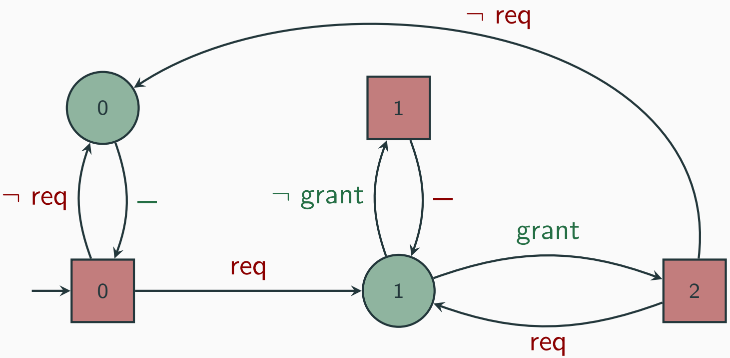


A Universal co-Büchi Automaton checking that every client is eventually satisfied.

How to Solve Reactive Synthesis?

- ➔ Convert the MSO specification to an ω-automaton
- ➔ Solve a game on this automaton

ω-regular games

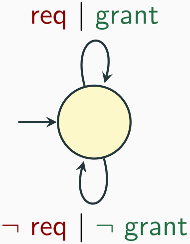


A parity game corresponding to $G(\text{req} \Rightarrow F(\text{grt}))$.

Models for Reactive Systems

Winning strategies in parity games are positional

Synchronous Sequential Transducers



- Automata with outputs
- Deterministically outputs a letter on reading a letter
- All states are accepting

Reactive Synthesis

Theorem (Büchi and Landweber 1969)

The synthesis problem from MSO specifications to Sequential Transducers is non-elementary (but decidable).

Proof steps

- Convert the MSO formula to an ω-automaton
- Solve a game on this automaton

Theorem [folklore]

The synthesis problem from Universal ω-Automata to Synchronous Sequential Transducers is ExpTime-c.

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Theorem (Pnueli and Rosner 1989)

The synthesis problem from LTL specifications to Sequential Transducers is 2-ExpTime-c.

Limitations

Observations

- ➔ Input and output alphabets are assumed to be finite sets
- ➔ Large alphabets require additional techniques

Back to our running example

- Set $C = \{1, \dots, n\}$ of users
- $\Sigma = \{\mathsf{req}_1, \dots, \mathsf{req}_n, \neg\mathsf{req}\}$ and $\Gamma = \{\mathsf{grt}_1, \dots, \mathsf{grt}_n, \neg\mathsf{grt}\}$
- Now, each user has a specific request
- Every request of client i is eventually granted:

$$\bigwedge_{1 \leq i \leq n} G\Big(\mathsf{req}_i \rightarrow F(\mathsf{grt}_i)\Big)$$

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➔ We consider the case where C is *infinite* and has some *structure*.

Objectives of the thesis

Main goal

Lift existing synthesis techniques to infinite alphabets

- ➔ Models for specifications and implementations
- ➔ Decidability and complexity of synthesis procedures
- ➔ Theoretical study of transducers over infinite alphabets

How to Represent Executions? Data Words

- *Data domain* $\mathcal{D} = (\mathbb{D}, \mathfrak{R}, \mathfrak{C})$: infinite set of *data* with predicates and constants
  - ➔ e.g. $(\mathbb{N}, =)$, $(\mathbb{Q}, <)$, $(\mathbb{N}, <, 0)$
- Σ finite alphabet of *labels*
- *Data words*: sequences of pairs $(a, d) \in \Sigma \times \mathbb{D}$

1	4	2	2	3	1	5	3	...
req	¬grt	req	grt	req	grt	¬req	grt	...

- $\Sigma = \{\text{req}, \text{grt}, \neg\text{req}, \neg\text{grt}\}$
- $\mathcal{D} = (\mathbb{N}, =)$

Extending Automata to Data Words

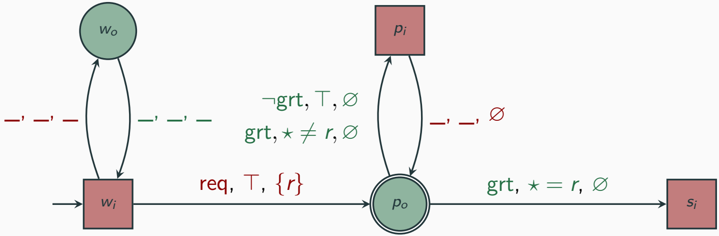
Register Automata (Kaminski and Francez 1994)

Finite automata with a finite set **R** of registers

- Store data
- Test register content

Transitions $q \xrightarrow{\sigma,\varphi,A} q'$

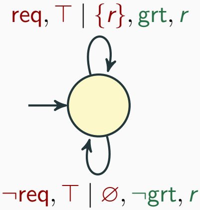
- $\sigma \in \Sigma$: label
- $\varphi \in \mathrm{QF}(R, \star)$: test
- $A \subseteq R$: assignment



An URA checking that every request is eventually granted.

Synchronous Sequential Register Transducers

- Transitions $q \xrightarrow{i,\varphi \mid A,o,r} q'$
  - i input letter, o output letter
  - φ test over $\star$
  - A registers assigned $\star$
  - r register whose content is output
- Sequentiality: tests are mutually exclusive



A register transducer immediately satisfying each user.

Outline

Part I: Reactive Synthesis

- ➔ Specifications: synchronous register automata
- ➔ Implementations: synchronous sequential register transducers
- ➔ Decidability border + compromise expressivity vs complexity

Part II: Computability

- ➔ Specifications: non-deterministic asynchronous register transducers
- ➔ Implementations: any algorithm
- ➔ Theory of asynchronous register transducers

Reactive Synthesis over Data Words

Synthesis of Register Transducers

$\mathcal{S}$: specification register automata

$\mathcal{I}$: synchronous sequential register transducers

Unbounded Synthesis Problem

Input: S a register automaton

Output:
- M a synchronous sequential register transducer such that $M \models S$ if it exists
- **No** otherwise

Theorem

The unbounded synthesis problem is undecidable for S given as a Universal Register Automaton with ≥ 3 registers, already over $(\mathbb{D}, =)$.

Register-Bounded Synthesis of Register Transducers

$\mathcal{S}$: specification register automata

$\mathcal{I}$: synchronous sequential register transducers with k registers

Register-Bounded Synthesis Problem

Input: S a register automaton, k a number of registers

Output:
- M a synchronous sequential register transducer with k registers (and arbitrarily many states) such that $M \models S$ if it exists
- **No** otherwise

Theorem

The register-bounded synthesis problem for S given as a Universal Register Automaton is in 2-ExpTime over $(\mathbb{D}, =)$ and $(\mathbb{Q}, <)$.

Reduction to the Finite Alphabet Case

Action Sequences

- Input actions: tests $\varphi \in \mathrm{QF}(R_k, \star)$ $\qquad R_k = \{r_1, \dots, r_k\}$
- Output actions: $(A, r) \in 2^{R_k} \times R_k$ $\qquad p \xrightarrow{i,\varphi | A,o,r} q$
- Action sequence $\alpha = a_1 a_2 \dots$

$$\mathrm{Comp}(\alpha) = \{w \in \mathbb{D}^\omega \mid \alpha \text{ can be performed on reading } w\}$$

Example

Sequence α	$\star \neq r_1, r_2$	$(\{r_1\}, r_1)$	$\star \neq r_1, r_2$	$(\{r_2\}, r_1)$	$\star = r_1$
Word w	1	1	2	1	1
Registers	(0,0)	(1,0)	(1,0)	(1,2)	(1,2)

➔ $w = 11211 \in \mathrm{Comp}(\alpha)$

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Word w'	1	1	1	1	1
Registers	(0,0)	(1,0)	(1,0)		

➔ $w' = 11111$ is not compatible with α

Reduction to the Finite Alphabet Case

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Word w	1	1	?		
Registers	(0,0)	(1,0)	(1,0)		

➔ α' is not feasible

The Case of Universal Specifications

Transfer Theorem

S is realisable by a sequential register transducer with k registers iff $W_{S,k} = \{\alpha \mid \mathrm{Comp}(\alpha) \subseteq S\}$ is realisable by a (register-free) sequential transducer.

- $W_{S,k}$ is ω-regular for S URA

$$W_{S,k} = \left(\mathrm{lab}\left(L_{S^c,k}\right)\right)^c$$

where $L_{S^c,k} = \{w \otimes \alpha \mid w \in \mathrm{Comp}(\alpha) \cap S^c\}$

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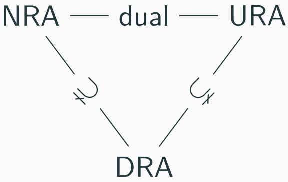
  where $L_{S^c,k} = \{w \otimes \alpha \mid w \in \mathsf{Comp}(\alpha) \cap S^c\}$
- Reduces to ω-regular synthesis

Theorem

The register-bounded synthesis problem for S given as a Universal Register Automaton is in 2-ExpTime over $(\mathbb{D}, =)$ and $(\mathbb{Q}, <)$.

Results

	URA	DRA	NRA	test-free NRA
Register-bounded synthesis	2EXPTIME	2EXPTIME	Undecidable ($k \geq 1$)	2EXPTIME
Unbounded Synthesis	Undecidable	EXPTIME-c	Undecidable	Open



The Case of Deterministic Specifications: $(\mathbb{N}, <)$

Theorem

The unbounded synthesis problem for S given as a Deterministic Register Automaton over $(\mathbb{N}, <)$ is undecidable.

➔ Simulate counting using antagonism between the players

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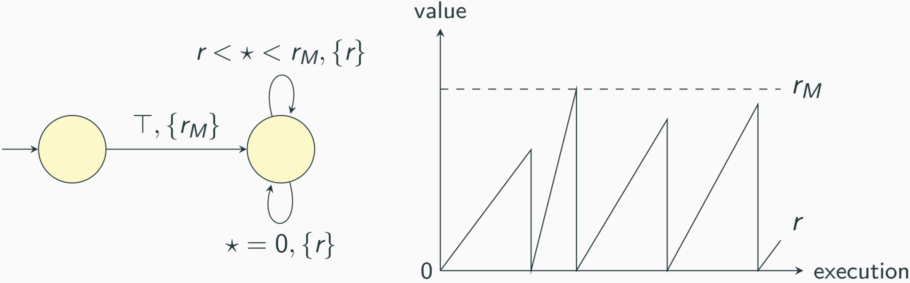
Non-regular behaviours



➔ The set of feasible action words is not regular

The Case of Deterministic Specifications: $(\mathbb{N}, <)$

Theorem

The unbounded synthesis problem for S given as a one-sided Deterministic Register Automaton over $(\mathbb{N}, <)$ is $\textsc{ExpTime}$-c.

- Target finite-memory implementations
  $\rightsquigarrow$ regular approximation is enough.

Summary

	URA	DRA	NRA	test-free NRA
Register-bounded synthesis	2ExpTime	2ExpTime	Undecidable ($k \geq 1$)	2ExpTime
Unbounded Synthesis	Undecidable	ExpTime-c	Undecidable	Open

Decidability picture over $(\mathbb{D}, =)$ and $(\mathbb{Q}, <)$

- Generalises to *oligomorphic data domains*
- Over $(\mathbb{N}, <)$, only the unbounded synthesis for one-sided DRA is known to be decidable

Related publications

- E., Filiot and Reynier (CONCUR 2019 and LMCS 2021). "Synthesis of Data Word Transducers"
- E., Filiot and Khalimov (STACS 2021). "Church Synthesis on Register Automata over Linearly Ordered Data Domains"

Closely Related Works

Synthesis from register automata

- Khalimov, Maderbacher, and Bloem 2018
- Khalimov and Kupferman 2019
- Ehlers, Seshia, and Kress-Gazit 2014

Synthesis from automata with arithmetic

Faran and Kupferman 2020

Synthesis from Logic of Repeating Values

Figueira, Majumdar, and Praveen 2020

Synthesis over timed automata

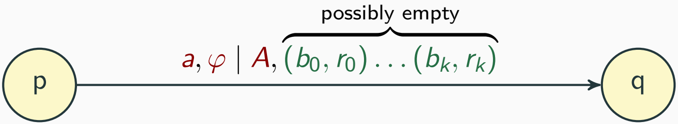
D'Souza and Madhusudan 2002

Computability over Data Words

Asynchronicity

- It can be worth waiting for additional input before outputting something
- Growing body of research on generalised transducers

Asynchronous Register Transducers



Asynchronicity

Theorem (Carayol and Löding 2015)

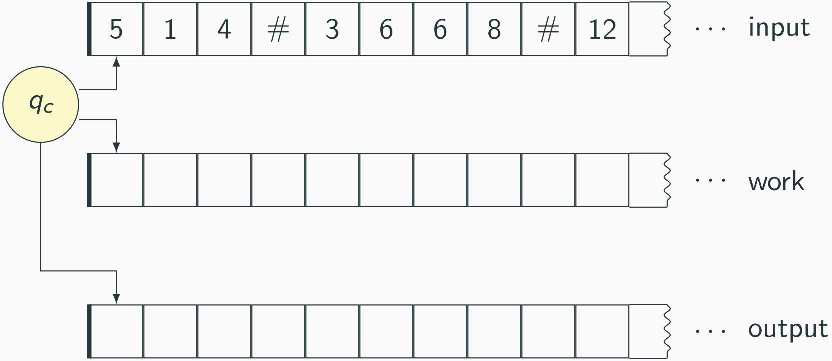
The synthesis problem from non-deterministic (register-free) asynchronous transducers to sequential ones is undecidable.

➔ Relax finite-memory requirement $\rightsquigarrow$ computable implementations.

Computability

Example

$f_{\text{swap}} : w_1 d_1 \# w_2 d_2 \# \cdots \mapsto d_1 w_1 \# d_2 w_2 \ldots$



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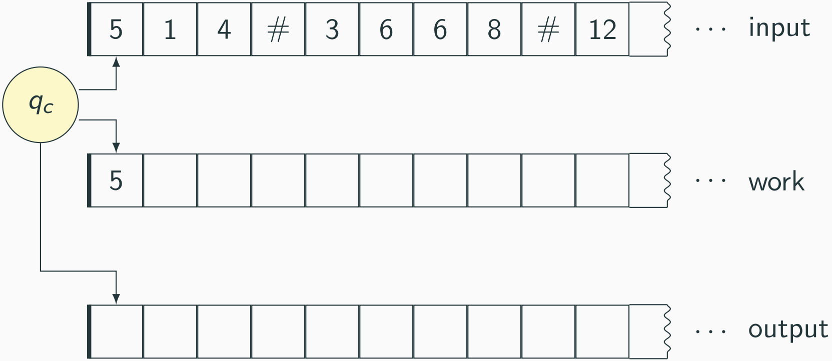

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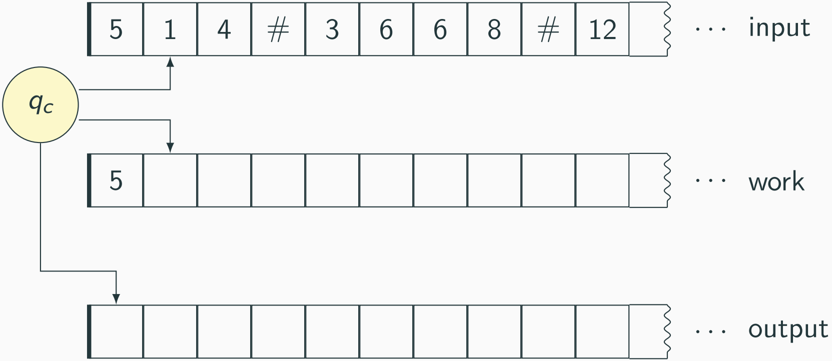

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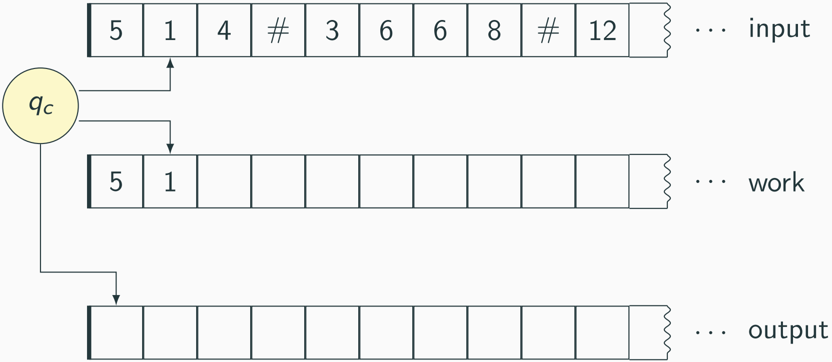

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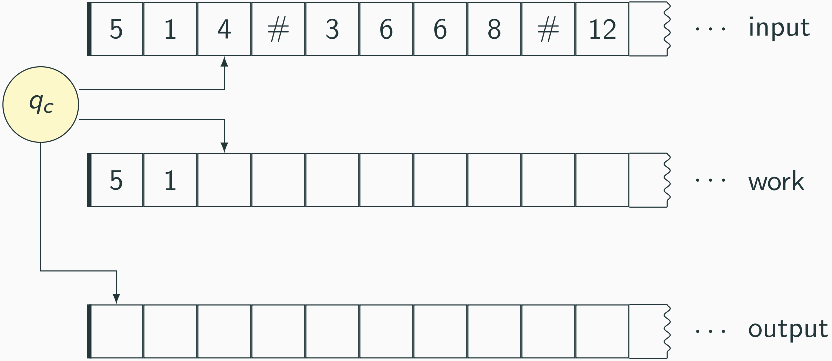

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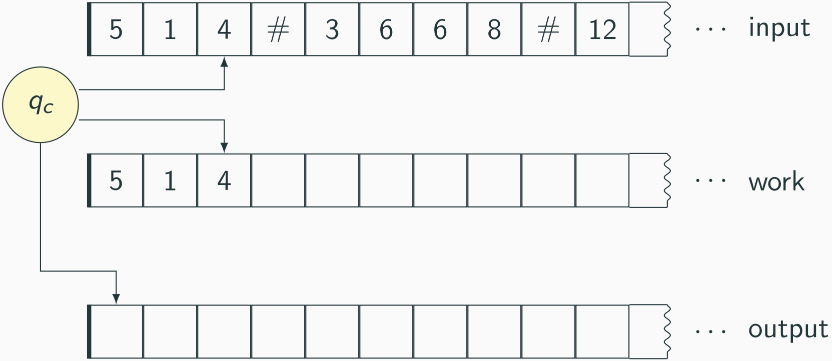

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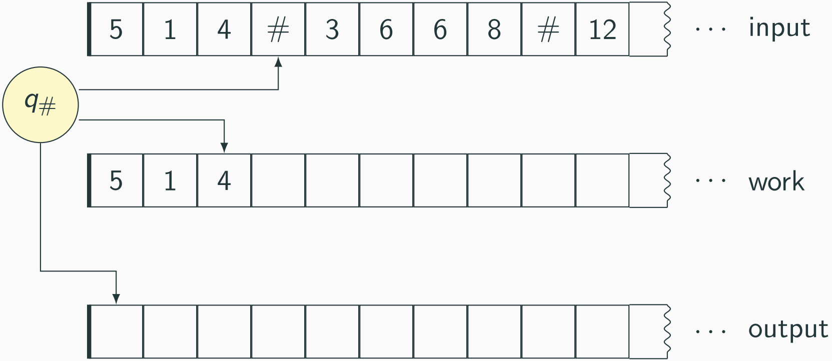

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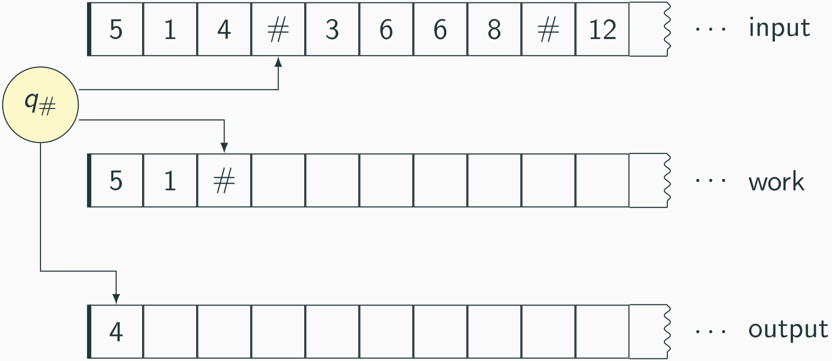

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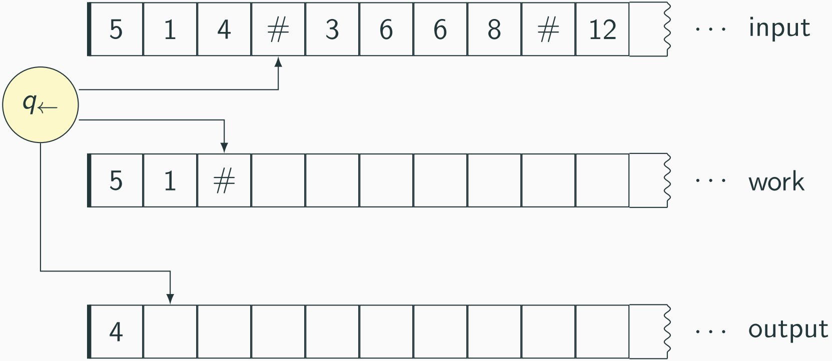

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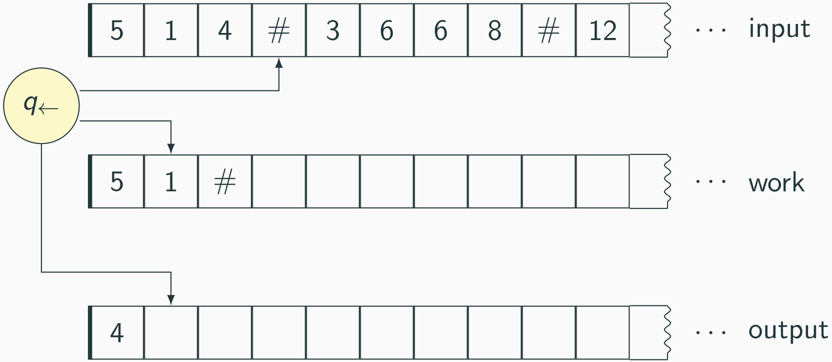

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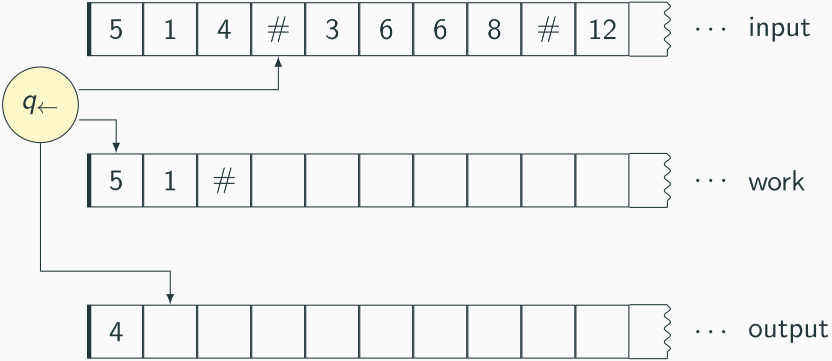

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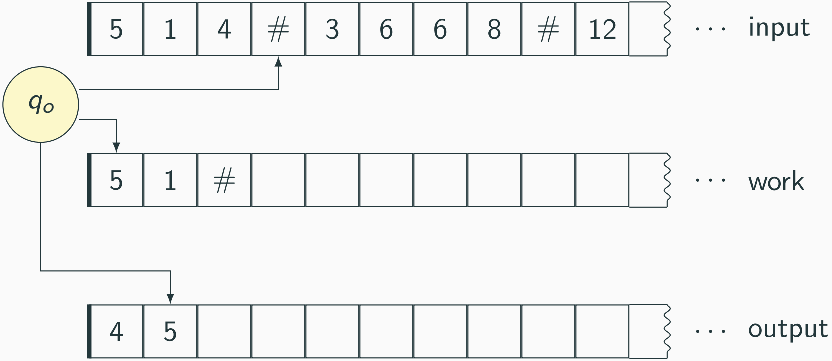

Computability

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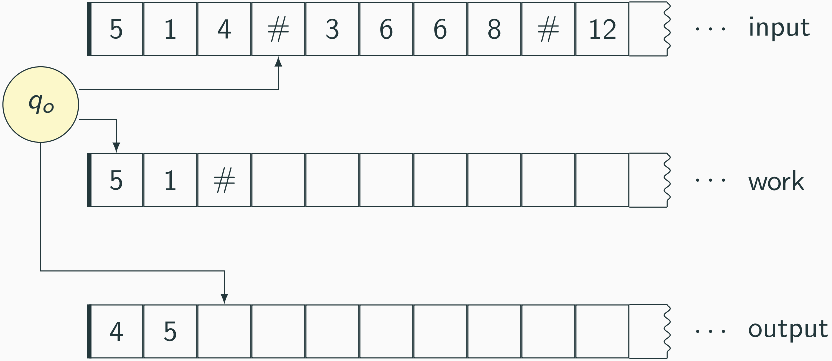

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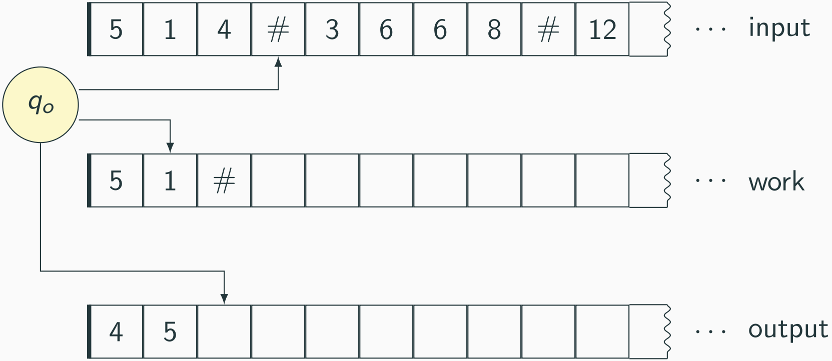

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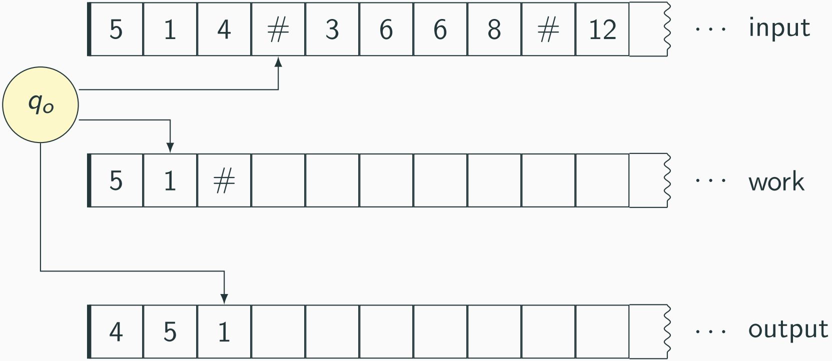

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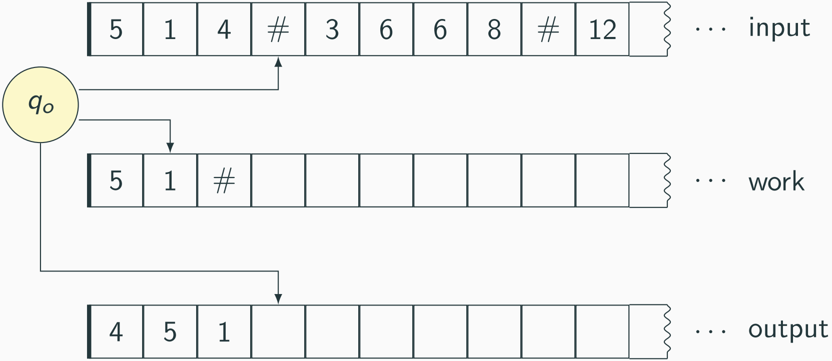

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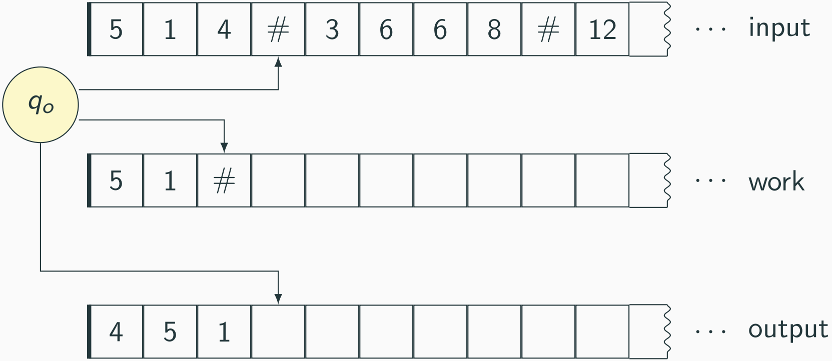

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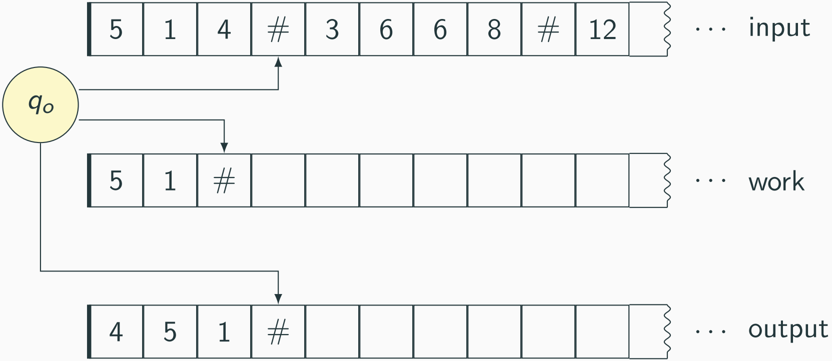

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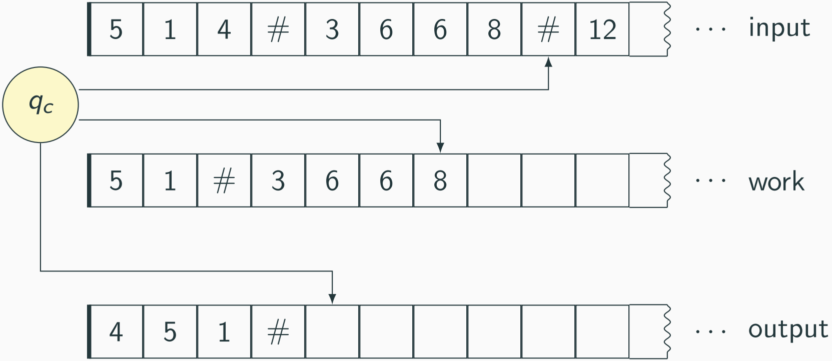

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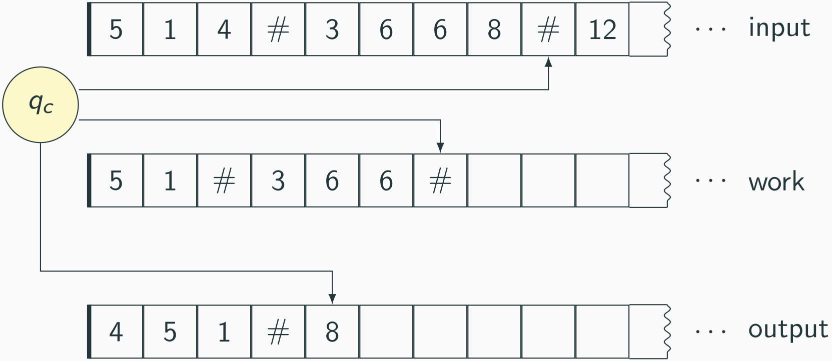

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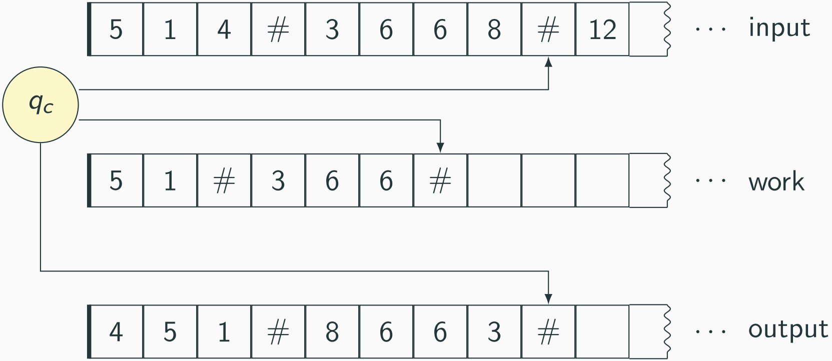

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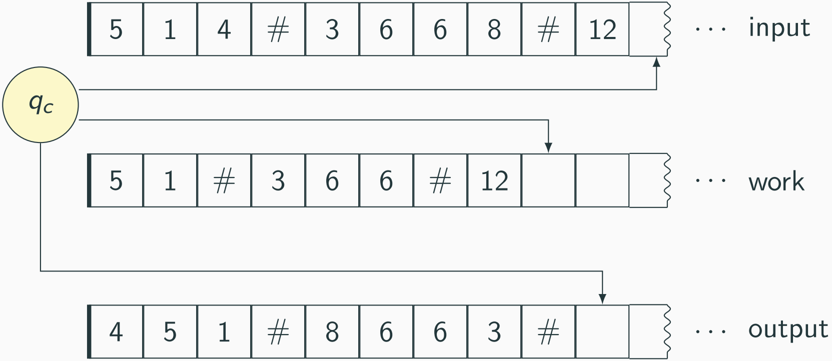

Computability

Three tape deterministic Turing machine

- Read-only one-way input tape
- Two-way working tape
- Write-only one-way output tape

M computes $f : \mathbb{D}^\omega \to \mathbb{D}^\omega$ if for all $x \in \mathrm{dom}(f)$,
M writes $f(x)$ in the limit

Theorem (Filiot and Winter 2021)

The synthesis problem of *computable functions* from non-deterministic asynchronous transducers over a *finite alphabet* is undecidable.

Computability

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Theorem (Filiot and Winter 2021)

The synthesis problem of *computable functions* from non-deterministic asynchronous transducers over a *finite alphabet* is undecidable.

➔ Restrict to functional specifications, i.e. specifications that define functions.

Computability

Example

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Computability

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$f_{\text{swap}} : w_1 d_1 \# w_2 d_2 \# \cdots \mapsto d_1 w_1 \# d_2 w_2 \ldots$

- ➔ Definable by a non-deterministic register transducer (in the manuscript)
- ➔ Computable, not by a sequential transducer

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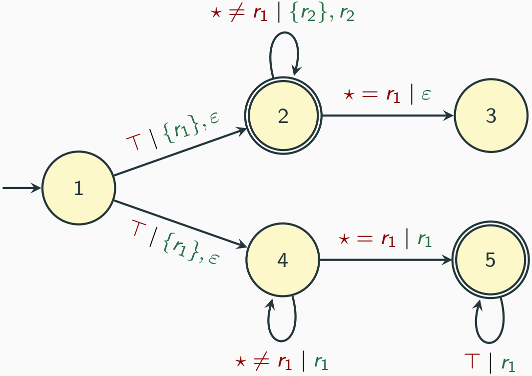
$f_{\text{swap}} : w_1 d_1 \# w_2 d_2 \# \cdots \mapsto d_1 w_1 \# d_2 w_2 \ldots$

Co-example

$$f_{\text{again}} : dw \mapsto \begin{cases} w & \text{if } d \notin w \\ d^\omega & \text{otherwise} \end{cases}$$



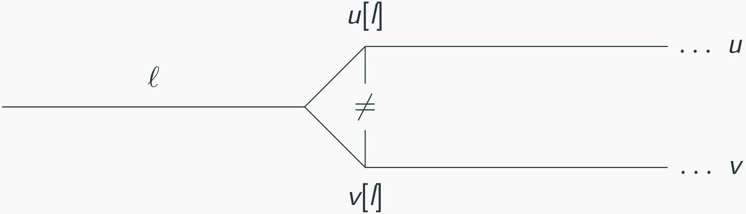
A register transducer defining f_{again}

Continuity

Cantor distance

For $u, v \in \mathbb{D}^\omega$, $d(u, v) = \begin{cases} 0 \text{ if } u = v \\ 2^{-|u \wedge v|} \text{otherwise} \end{cases}$

$u \wedge v$: longest common prefix ℓ of u and v



Continuous function

$f : \mathbb{D}^\omega \to \mathbb{D}^\omega$ is *continuous* if:

$$\lim_{n\infty} f(x_n) = f(\lim_{n\infty}(x_n))$$

Computability over finite alphabets

Theorem (Dave et al. 2019)
Let $f\colon \Sigma^\omega \to \Sigma^\omega$ be a function definable by a non-deterministic transducer over a *finite alphabet*. Then f is continuous iff it is computable.

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Theorem (Dave et al. 2019)
Computability of functions defined by nondeterministic transducers is decidable in $\textsc{PTime}$.

Computability and Continuity

Computability

$f : \mathbb{D}^\omega \to \mathbb{D}^\omega$ computable: deterministic Turing machine that outputs $f(x)$ in the limit.

Continuity

$$\lim_{n\infty} f(x_n) = f(\lim_{n\infty}(x_n))$$

Computability $\Rightarrow$ Continuity

Deterministic machine: when *reading* head is at position k, the output only depends on the k first letters.

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Computability $\Rightarrow$ Continuity

Deterministic machine: when *reading* head is at position k, the output only depends on the k first letters.

- The other implication does not always hold.

Continuity and computability

Theorem

A function defined by a non-deterministic register transducer over oligomorphic domains or $(\mathbb{N}, <)$ *is computable iff it is continuous.*

Computability $\Rightarrow$ Continuity is proved as before.

Continuity $\Rightarrow$ Computability: requires to determine the next letter.

Next-letter problem

Input: $u, v \in \mathbb{D}^*$

Output: $d \in \mathbb{D}$ s.t. $\forall y \in \mathbb{D}^\omega$ s.t. $u \cdot y \in \mathrm{dom}(f)$, $v \cdot d \preceq f(u \cdot y)$ if it exists

`No` otherwise

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`No` otherwise

Theorem

For functions defined by register transducers over oligomorphic domains or $(\mathbb{N}, <)$, deciding computability is $\textsc{PSpace}$-complete.

Summary

➔ Continuity $\equiv$ computability for functions defined by non-deterministic register transducers, over a large class of domains

➔ This is decidable.

Related publications

- E., Filiot and Reynier (FoSSaCS 2020). "On Computability of Data Word Functions Defined by Transducers"
- E., Filiot, *Lhote* and Reynier (submitted to LMCS). "Computability of Data-Word Transductions over Different Data Domains"

Perspectives

Reactive Synthesis

- Good-for-games register automata
- Register-bounded synthesis over $(\mathbb{N}, <, 0)$
- Synthesis from logical formalisms: $FO_2[<_p, \sim]$, $FO_2[<_p, <_d]$

Computability

- Generalise to other data domains and two-way models
- Lift the functionality requirement: automatic specifications

Going Further

- Explore other formalisms than register automata
- Minimisation and learning of non-deterministic transducers

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