

Lecture 5: Three More Models

Models of Computation

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Ph.D. Program, Advanced Courses Period

Gran Sasso Science Institute

L'Aquila, Italy

July 11, 2025

Course overview

Monday, July 7 10.30 – 12.30	Tuesday, July 8 10.30 – 12.30	Wednesday, July 9 10.30 – 12.30	Thursday, July 10 10.30 – 12.30	Friday, July 11
<i>intro</i>	<i>classic models</i>			<i>additional models</i>
Introduction to Computability	Machine Models	Recursive Functions	Lambda Calculus	
computation and decision problems, from logic to computability, overview of models of computation relevance of MoCs	Post Machines, typical features, Turing's analysis of human computers, Turing machines, basic recursion theory	primitive recursive functions, Gödel–Herbrand recursive functions, partial recursive funct's, partial recursive = Turing-computable, Church's Thesis	λ -terms, β -reduction, λ -definable functions, partial recursive = λ -definable = Turing computable	
	<i>imperative programming</i>	<i>algebraic programming</i>	<i>functional programming</i>	
				14.30 – 16.30
				Three more Models of Computation
				Post's Correspondence Problem, Interaction-Nets, Fractran
				comparing computational power

Some Models of Computation

machine model	mathematical model	sort
Turing machine Post machine register machine	Combinatory Logic λ -calculus Herbrand–Gödel recursive functions partial-recursive/ μ -recursive functions Post canonical system (tag system) Post's Correspondence Problem Markov algorithms Lindenmayer systems	<i>classical</i>
	Fractran	<i>less well known</i>
cellular automata neural networks	term rewrite systems interaction nets logic-based models of computation concurrency and process algebra ζ -calculus evolutionary programming/genetic algorithms	<i>modern</i>
	abstract state machines	
	hypercomputation	<i>speculative</i>
	quantum computing bio-computing reversible computing	<i>physics-/biology- inspired</i>

Overview

- ▶ **Post's Correspondence Problem** (by **Emil Post**, 1946, [5])

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- ▶ Compare computational power of models of computation
- ▶ [Interaction Nets](#) (by [Yves Lafont](#), 1990, [[4](#)])
- ▶ [Fractran](#) (by [John Horton Conway](#), 1987, [[2](#)])

Post's Correspondence Problem

Emil Leon Post:

- ▶ article:
 - ▶ "A Variant of a Recursively Unsolvable Problem"
Bulletin of the American Mathematical Society, 1946.

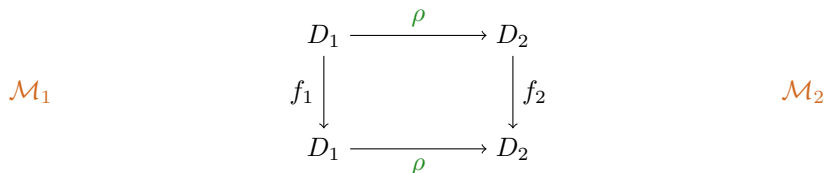
Comparing computational power via encodings

- ▶ Simulation of models of computation $\mathcal{M}_1 = \langle D_1, \mathcal{F}_1 \rangle$, $\mathcal{M}_2 = \langle D_2, \mathcal{F}_2 \rangle$:

Comparing computational power via encodings

► Simulation of functions:

function f_2 *simulates* function f_1 via *encoding* ρ if:

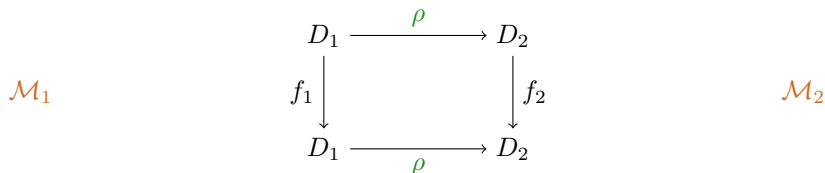


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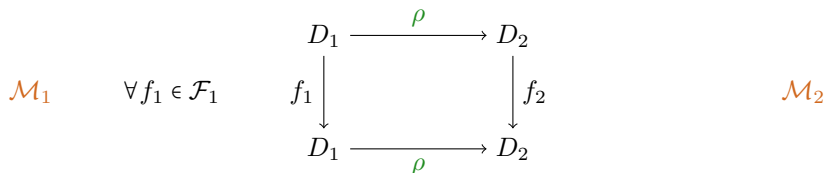


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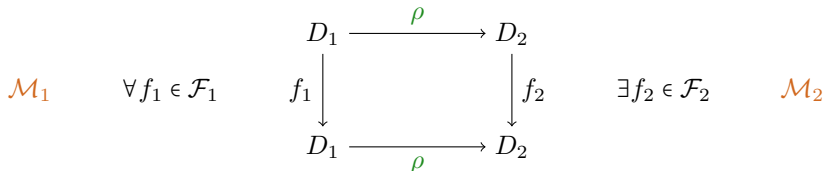


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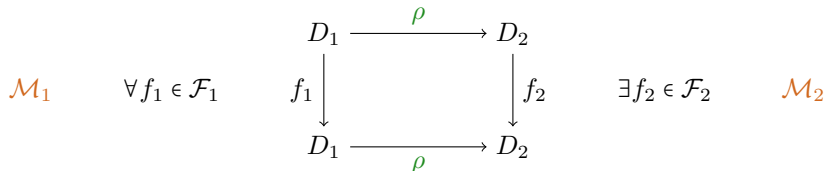


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 \mathcal{M}_2 *can simulate* \mathcal{M}_1 via ρ ($\mathcal{M}_1 \precsim_\rho \mathcal{M}_2$), if:

$$\forall f_1 \in \mathcal{F}_1 \exists f_2 \in \mathcal{F}_2 (f_2 \text{ simulates } f_1 \text{ via } \rho)$$

Weak requirements on encodings (Boker/Dershowitz)

Traditional requirements on encodings are:

- ▶ *informally computable/effective/mechanizable in principle*
- ▶ *computable* with respect to a specific model (Turing machine, ...)

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Definition (**power subsumption** pre-order [Boker/Dershowitz 2006 [1]])

- $\mathcal{M}_1 \lesssim \mathcal{M}_2$ if: there is an **injective** ρ such that $\mathcal{M}_1 \lesssim_{\rho} \mathcal{M}_2$
- $\mathcal{M}_1 \lesssim_{\text{bijective}} \mathcal{M}_2$ if: there is a **bijective** ρ such that $\mathcal{M}_1 \lesssim_{\rho} \mathcal{M}_2$

Anomalies for decision models

However, we found anomalies of these definitions.

$\mathcal{M} = \langle D, \mathcal{F} \rangle$ is a *decision model* if $\{0, 1\} \subseteq D$, $\forall f \in \mathcal{F} (f[D] \subseteq \{0, 1\})$.

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Theorem (Endrullis/G/Hendriks, [3])

Let Σ and Γ with $\{0, 1\} \subseteq \Sigma, \Gamma$ be alphabets.

Then for every countable decision model $\mathcal{M} = \langle \Sigma^*, \mathcal{F} \rangle$, it holds:

$$\mathcal{M} \lesssim \text{DFA}(\Gamma) \qquad \mathcal{M} \lesssim_{\text{bijective}} \text{DFA}(\Gamma)$$

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$\text{TMD}(\Sigma)$: class of Turing machine deciders with input alphabet Σ

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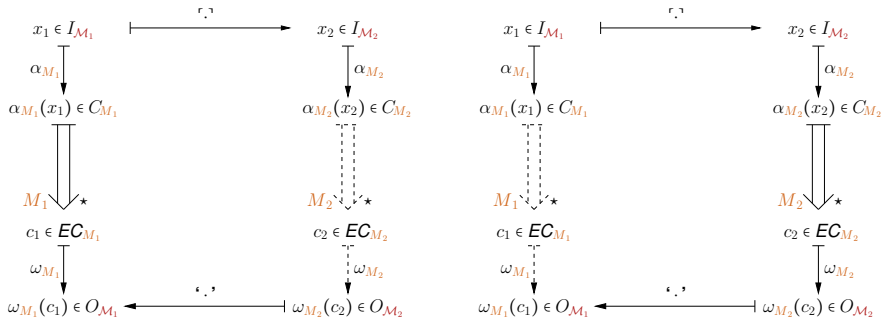
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These anomalies for **decision models** and **bijective encodings**:

- ▶ depend on **uncomputable encodings**
- ▶ can be extended to **some** moc's with unbounded output domain
- ▶ but **do not extend** to **all** moc's

Simulations between models of computation

models $M_1 \in \mathcal{M}_1$ and $M_2 \in \mathcal{M}_2$ **simulate each other** with respect to **computable** coding $\ulcorner \cdot \urcorner : I_{\mathcal{M}_1} \rightarrow I_{\mathcal{M}_2}$ and decoding $\lceil \cdot \rceil : O_{\mathcal{M}_2} \rightarrow O_{\mathcal{M}_1}$ if:



(defines a **Galois connection**)

Models of computation, viewed abstractly

A(n abstractly viewed) model of computation (MoC) is a class \mathcal{M} of machines/systems/. . . such that every $M \in \mathcal{M}$ it holds:

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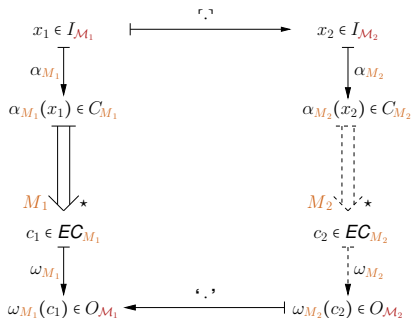
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- ▷ M has a partial output function $\omega_M : EC_M \rightarrow O_{\mathcal{M}}$, which maps some end-configurations of M to output objects of M ; ω_M is computable, and membership of end-configurations in $\text{dom}(\omega_M)$ is decidable.

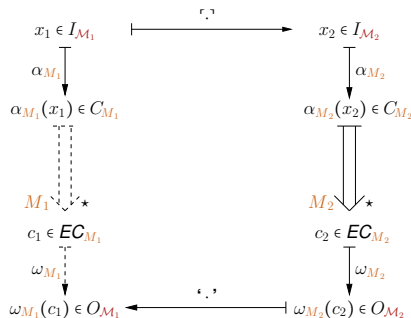
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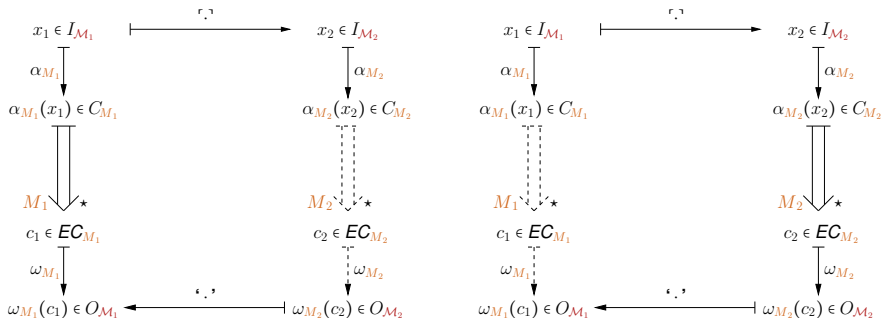
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Comparing Computational Power of MoC's

Definition

Let \mathcal{M}_1 and \mathcal{M}_2 be MoC's.

- ① The computational power of \mathcal{M}_1 is subsumed by that of \mathcal{M}_2 , denoted symbolically by $\mathcal{M}_1 \leq \mathcal{M}_2$, if:

(\exists a pair $\langle \ulcorner \cdot \urcorner, \lceil \cdot \rceil \rangle$ of computable encoding and decoding functions $\ulcorner \cdot \urcorner : I_{\mathcal{M}_1} \rightarrow I_{\mathcal{M}_2}$ and $\lceil \cdot \rceil : O_{\mathcal{M}_2} \rightarrow O_{\mathcal{M}_1}$

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- 2 The computational power of \mathcal{M}_1 is equivalent to that of \mathcal{M}_2 , denoted by $\mathcal{M}_1 \sim \mathcal{M}_2$, if both $\mathcal{M}_1 \leq \mathcal{M}_2$ and $\mathcal{M}_2 \leq \mathcal{M}_1$ hold.

Comparing Computational Power of MoC's

Theorem

For all models \mathcal{M}_1 and \mathcal{M}_2 , and encoding and decoding functions $\lceil \cdot \rceil : I_{\mathcal{M}_1} \rightarrow I_{\mathcal{M}_2}$ and $\lceil \cdot \rceil : O_{\mathcal{M}_2} \rightarrow O_{\mathcal{M}_1}$ it holds:

$$\mathcal{M}_1 \leq_{(\lceil \cdot \rceil, \lceil \cdot \rceil)} \mathcal{M}_2 \implies \mathcal{F}(\mathcal{M}_1) \subseteq \{ \lceil \cdot \rceil \circ f \circ \lceil \cdot \rceil \mid f \in \mathcal{F}(\mathcal{M}_2) \}.$$

Turing completeness and equivalence

By $\mathcal{TM}(\Sigma)$ we mean the model of Turing machines over input alphabet Σ .

Definition

Let \mathcal{M} a model of computation.

\mathcal{M} is **Turing-complete** if $\mathcal{TM}(\Sigma) \leq \mathcal{M}$ for some alphabet Σ with $\Sigma \neq \emptyset$.

\mathcal{M} is **Turing-equivalent** if $\mathcal{M} \sim \mathcal{TM}(\Sigma)$ for some alphabet $\Sigma \neq \emptyset$.

Interaction Nets

Yves Lafont (1990) [4] ([link](#) [pdf](#)) proposed:

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Analogy with:

- ▶ electric circuits:
 - ▶ agents $\hat{=}$ gates,
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Analogy with:

- ▶ electric circuits:
 - ▶ agents $\hat{=}$ gates,
 - ▶ edges $\hat{=}$ wires
- ▶ agents as computation entities:
 - ▶ interaction rules specify behavior

Fractran

John Horton Conway:

- ▶ article:
 - ▶ **FRACTRAN:**
A Simple Universal Programming Language for Arithmetic
- ▶ talk video:
 - ▶ "Fractran: A Ridiculous Logical Language"

Summary

- ▶ Post's Correspondence Problem (by Emil Post, 1946, [5])
- ▶ Compare computational power of models of computation
- ▶ Interaction Nets (by Yves Lafont, 1990, [4])
- ▶ Fractran (by John Horton Conway, 1987, [2])

Some Models of Computation

machine model	mathematical model	sort
Turing machine Post machine register machine	Combinatory Logic λ -calculus Herbrand–Gödel recursive functions partial-recursive/ μ -recursive functions Post canonical system (tag system) Post's Correspondence Problem Markov algorithms Lindenmayer systems	<i>classical</i>
	Fractran	<i>less well known</i>
cellular automata neural networks	term rewrite systems interaction nets logic-based models of computation concurrency and process algebra ζ -calculus evolutionary programming/genetic algorithms	<i>modern</i>
	abstract state machines	
	hypercomputation	<i>speculative</i>
	quantum computing bio-computing reversible computing	<i>physics-/biology- inspired</i>

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References I



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Comparing computational power.

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