



# Limits of Computation

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9 - More non-computable problems  
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Last time

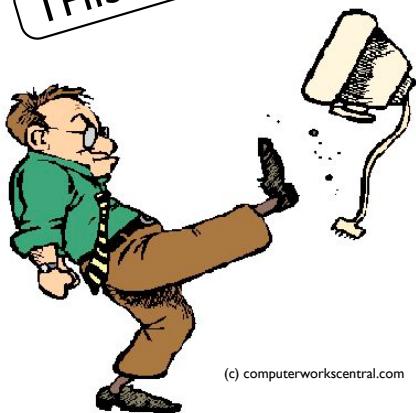
- we have seen that the *Halting Problem* for WHILE-programs cannot be decided by a WHILE-program, but ...
- ... can we say something at least?



# More undecidable problems

- we show that *Halting Problem* is semi-decidable (and explain what that means)
- next, we generalise the *Halting Problem* and the proof of its undecidability
  - to prove Rice's Theorem
- Other undecidable problem:
  - *Tiling Problem*
- and non-computable function:
  - *Busy Beaver*

THIS TIME



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## WHILE Semi-Decidability

**Definition 9.1.** A set  $A \subseteq \mathbb{D}$  is WHILE-semi-decidable if, and only if, there exists a WHILE-program  $p$  such that for all  $d \in \mathbb{D}$  the following holds:  $d \in A$  if, and only if,  $\llbracket p \rrbracket^{\text{WHILE}}(d) = \text{true}$ .

So the “membership test” may not terminate if the answer is “false”, it only works reliably for “half” of the cases, hence the term “semi-decidability”.

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# HALT is WHILE semi-decidable

**Theorem 9.1.** *The Halting problem (for WHILE-programs) HALT is WHILE-semi-decidable.*

**Proof** The “semi-decision procedure” is as follows:

```
sd read PD {
    Res := <u> PD; (* call self-interpreter *)
    X := true          (* X is true *)
}
write X
```

*u is universal WHILE-program  
(self-interpreter)*

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## Decidable V Semi-decidable

**Theorem 9.2.** 1. Any finite set  $A \subseteq \mathbb{D}$  is WHILE-decidable.

2. If  $A \subseteq \mathbb{D}$  is WHILE-decidable then so is  $\mathbb{D} \setminus A$ , its complement in  $\mathbb{D}$ .  
 → *is “set difference”*  
 → *read: “then so is its complement”*

3. Any WHILE decidable set is WHILE-semi-decidable.

4. A problem (set)  $A \subseteq \mathbb{D}$  is WHILE-decidable if, and only if, both  $A$  and its complement,  $\mathbb{D} \setminus A$ , are WHILE-semi-decidable.

Proofs as exercise!

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## Generalising the Halting Problem

- We have shown (*by contradiction*) that the *Halting Problem* cannot be decided by a WHILE program.
- The *Halting Problem* is a problem about a property of WHILE-programs, namely whether they terminate (*for specific input*).
- We now generalise to all (“*interesting*”) properties (of a certain kind) of WHILE-programs.

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### “Interesting” Properties of Programs

informally

- “*interesting*” here means:  
*non-trivial & extensional*.
- A *non-trivial* property is one that not all programs have, but that at least one program has.
- An *extensional* program property is one that depends exclusively on the input-output behaviour of the program, i.e. its *semantics*.

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# “Interesting” Properties of Programs

formally

**Definition 9.3.** A *program property*  $A$  is a subset of WHILE-programs.

A program property  $A$  is *non-trivial* if  $\{\} \neq A \neq \text{WHILE-programs}$ .

A program property is *extensional* if for all  $p, q \in \text{WHILE-programs}$  such that  $\llbracket p \rrbracket^{\text{WHILE}} = \llbracket q \rrbracket^{\text{WHILE}}$  it holds that  $p \in A$  if and only if  $q \in A$ .

This says that:

if  $p$  has property  $A$  and its semantics is the same as that of  $q$ , then also  $q$  must have property  $A$ .

If  $p$  does not have property  $A$ , and its semantics is the same as that of  $q$ , then also  $q$  does not have property  $A$ .

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## Rice’s Theorem



Henry Gordon Rice (1920–2003)

### Rice’s Theorem:

*If  $A$  is an extensional and non-trivial program property  
then  $A$  is undecidable.*

Proof by contradiction:

Assume  $A$  is decidable,  
then show that the *Halting Problem* is decidable.

contradiction



# Proof of Rice's Thm.

First we define two programs we need:

```
diverge read X {
    while true {
    }
}
write Y
```

By non-triviality of  $A$  we know that there is a program that is not in  $A$ . Let us call this program  $\text{comp}$ .

$\llbracket \text{diverge} \rrbracket^{\text{WHILE}}(d) = \perp$  for any  $d \in \mathbb{D}$ .

Now assume  $A$  contains  $\text{diverge}$

if not, swap role of  $A$  and its complement

$\text{diverge} \in A$

$\text{comp} \notin A$

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## Proof of Rice's Thm (II)

We wish to decide whether  $\llbracket p \rrbracket^{\text{WHILE}}(e) \neq \perp$ .

e as tree literal

```
q read X {
    Y := <p> "e", (* run p on value e *)
    Res := <comp> X   (* run comp on input X *)
}
write Res
```

We now consider the behaviour of  $q$  and whether it is in  $A$  or not. If  $\llbracket p \rrbracket^{\text{WHILE}}(e) = \perp$  then clearly  $\llbracket q \rrbracket^{\text{WHILE}}(d) = \perp$  for all  $d \in \mathbb{D}$ . On the other hand, if  $\llbracket p \rrbracket^{\text{WHILE}}(e) \downarrow$  then  $\llbracket q \rrbracket^{\text{WHILE}}(d) = \llbracket \text{comp} \rrbracket^{\text{WHILE}}(d)$  for all  $d \in \mathbb{D}$ . Therefore we get that

$$\llbracket q \rrbracket^{\text{WHILE}} = \begin{cases} \llbracket \text{diverge} \rrbracket^{\text{WHILE}} & \text{if } \llbracket p \rrbracket^{\text{WHILE}}(e) = \perp \\ \llbracket \text{comp} \rrbracket^{\text{WHILE}} & \text{if } \llbracket p \rrbracket^{\text{WHILE}}(e) \neq \perp \end{cases}$$



# Proof of Rice's Thm (III)

$$[\![q]\!]^{\text{WHILE}} = \begin{cases} [\![\text{diverge}]\!]^{\text{WHILE}} & \text{if } [\![p]\!]^{\text{WHILE}}(e) = \perp \\ [\![\text{comp}]\!]^{\text{WHILE}} & \text{if } [\![p]\!]^{\text{WHILE}}(e) \neq \perp \end{cases} \quad \text{implies}$$

$$\begin{array}{lll} \text{diverge} \in A & \text{iff} & q \in A & \text{if } [\![p]\!]^{\text{WHILE}}(e) = \perp \\ \text{comp} \notin A & \text{iff} & q \notin A & \text{if } [\![p]\!]^{\text{WHILE}}(e) \neq \perp \end{array}$$

*because of our assumptions*

*because A is extensional*

*contradiction*

So if we can decide A, we can decide HALT



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# Tiling Problem



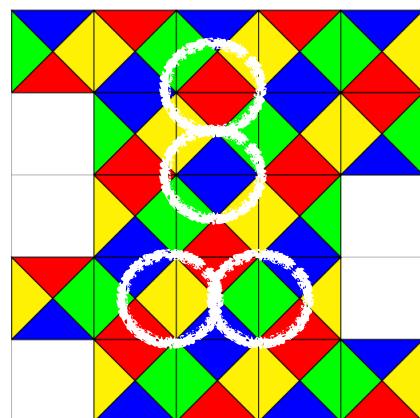
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Given an infinite supply of tiles that are of a finite type (here: 1,2), can we tile any **arbitrary large** quadratic floor (i.e. the plane) so that the patterns of all tiles **match** (in all 4 directions)?

*you are not allowed to rotate the tiles, rotation requires a new tile type*

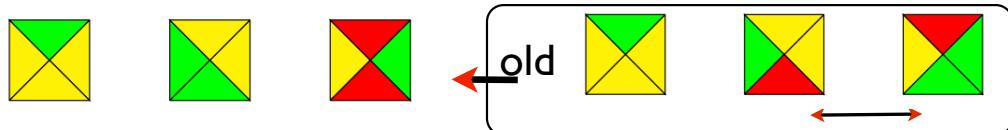


**DECISION PROBLEM**

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## Tiling Problem (cont'd)



- Note that swapping South-facing colours of tile type 2 and 3 as above will mean we cannot even tile a 3x3 square. (*Try it out yourself! Exercises.*)
- The tiling problem for arbitrary finite sets of tile types is **undecidable**.

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## Tiling Problem is Hard

- **1961: H. Wang** presents an algorithm that decides whether any given finite set of tile types can tile the plane. In his proof he assumed that any set that could tile the plane would be able to do so periodically (ie with a repeating pattern like a wallpaper)
- **1966: Robert Berger** proved **Wang's conjecture wrong**. He presented a case where the tiles would only tile the plane without repeating pattern, allegedly using 20,426 distinct tile shapes! "Undecidability of the domino problem", Memoirs of the AMS in 1966.

current record is using  
only 13 tiles

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# Undecidability of Tiling the Plane

- tiling problem for a *fixed size floor*,  $n \times n$ , is clearly decidable (check all tilings);
- infinity of the plane alone is not the reason why tiling of the plane is undecidable;
- How to prove undecidability?  
if the *Tiling Problem* was decidable so would be the *Halting Problem* for *Turing Machines* (encode sequence of *Turing Machine* states by tiles which match if they are successor states in a step).

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## Reduction

- already several times this principle was used:  
*to show that a problem is undecidable (non-computable), argue that if it was decidable (computable) then we could decide (compute) the Halting Problem.*
- *Halting Problem* is “at most as hard” than these other problems.
- This is called a (computable) problem *reduction*.
- We have seen that the *Halting Problem* can be reduced to any *non-trivial & extensional* program *property* or the Tiling problem. Thus those can’t be decidable either.

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informally

# Reduction

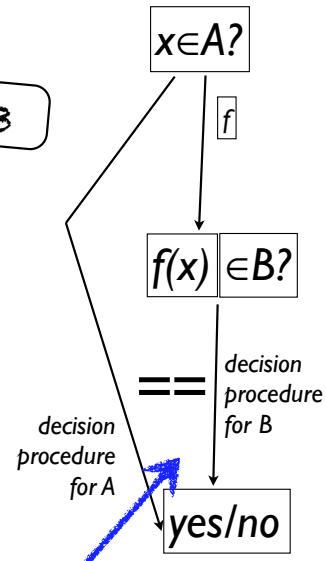
from A to B

- Assume  $A \subseteq X$  and  $B \subseteq Y$ .
- The decision problem  $x \in A?$  can be reduced to the decision problem  $y \in B? \dots$
- ...if we find a computable (total) function  $f: X \rightarrow Y$  such that

$x \in A$  “holds exactly if”  $f(x) \in B$

iff

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# Reduction

formally

**Definition 9.4 (Reduction).** Suppose one is given  $A \subseteq X$  and  $B \subseteq Y$ . Define  $A$  to be *effectively reducible* to  $B$  if there is a total computable function  $f: X \rightarrow Y$  such that for all  $x \in X$ , we have  $x \in A$  if, and only if,  $f(x) \in B$ .

Symbolically we write this relation as  $A \leq_{\text{rec}} B$  (“ $A$  is effectively reducible to  $B$ ”).

$B$  is at least as hard as  $A$

**Theorem 9.4.** If  $A \leq_{\text{rec}} B$  and  $B$  is decidable then  $A$  is also decidable.

Contrapositively, if  $A \leq_{\text{rec}} B$  and  $A$  is undecidable then  $B$  is also undecidable.

Proof in Exercises.



## Other undecidable Problems

- Decision Problem: do languages accepted by two given context free grammars (CFGs) overlap?
- Decision Problem: is a CFG ambiguous?
- Decision Problem: does a CFG generate *all* words over a given alphabet?
- Rewriting problem (does one string rewrite into another one using a set of given rewrite rules)
- Type Checking/Inference for functional languages with polymorphic types, where the *type of all types* is *a type itself*, is undecidable.

Joe Wells: "Typability and Type-checking in System F are equivalent and undecidable", Annals of Pure and Applied Logic, 1999.



Haskell  
avoids this  
“type of all  
types”

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## Other (famous) undecidable Problems in Mathematics

- Given a system of equations with integer coefficients, does it have an integer solution?
- word problem for groups
- Hilbert's *Entscheidungsproblem* (is a given formulae valid in arithmetic?)

proved undecidable by Matiyasevic in 1977

There are many others...

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# Dealing with Undecidability

- use approximation of problem (if appropriate)
- give up on uniformity (restricted input)
- give up on (full) automation
- be content solving a simpler problem

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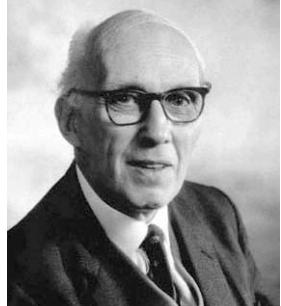
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a non-computable function on numbers

## Busy Beaver



Tibor Radó  
(1895 -1965)

- “Can we compute the function BB that for every input number  $n$  returns the greatest number that can be outputted by any WHILE-program that is (as syntactic string) at most  $n$  characters long (when run with input 0)?”
- T. Radó in his 1962 paper "On Non-Computable Functions" (using Turing-Machines where  $n$  is the number of states)

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# Busy Beaver Research



- In theoretical computer science the *Busy Beaver Problem* for *Turing Machines* has been a challenge some researchers could not keep away from.
- Marxen and Buntrock “*Attacking the Busy Beaver 5*”, *Bulletin of the EATCS*, No. 40, 1990, pp. 247-251, used a significant amount of resources to compute  $BB(5)$  for TMs:

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## $BB(5)$ Attack

- They used a brute-force simulation technique going through 99.7% of all 88 million 5-state TMs but spending much thought on how to speed up simulation (using “macro-machines” that can simulate several steps in one).
- C program of about 8,000 lines
- it took 10 days to run on a 33MHz CPU
- Result:  $BB(5) \geq 4098$

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# END

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Next time:  
Is there a program that can return “itself”?

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