Recursion Theory

Joost J. Joosten

Institute for Logic Language and Computation University of Amsterdam Plantage Muidergracht 24 1018 TV Amsterdam Room P 3.26, +31 20 5256095 jjoosten@phil.uu.nl www.phil.uu.nl/~jjoosten

Tuesday November 14, 16.00-17.00

- Tuesday November 14, 16.00-17.00
- P 327

- Tuesday November 14, 16.00-17.00
- P 327
- Intervals in the Medvedev lattice

- Tuesday November 14, 16.00-17.00
- P 327
- Intervals in the Medvedev lattice
- Link intuitionism/computability theory

- Tuesday November 14, 16.00-17.00
- P 327
- Intervals in the Medvedev lattice
- Link intuitionism/computability theory
- Do come!

- Tuesday November 14, 16.00-17.00
- P 327
- Intervals in the Medvedev lattice
- Link intuitionism/computability theory
- Do come!
- Later (April-June) there are lectures by Hamkins on

- Tuesday November 14, 16.00-17.00
- P 327
- Intervals in the Medvedev lattice
- Link intuitionism/computability theory
- Do come!
- Later (April-June) there are lectures by Hamkins on
- Advanced Topics in Recursion Theory

- Tuesday November 14, 16.00-17.00
- P 327
- Intervals in the Medvedev lattice
- Link intuitionism/computability theory
- Do come!
- Later (April-June) there are lectures by Hamkins on
- Advanced Topics in Recursion Theory
- And projects in June

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either $K \leq_m A$ or $K \leq_m \overline{A}$

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either *K* ≤_{*m*} *A* or
 $K ≤_m \overline{A}$
- Case distinction \varnothing has no code in A, or it has

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either $K ≤_m A$ or
 $K ≤_m \overline{A}$
- Case distinction \varnothing has no code in A, or it has
- By assumption, there is some $e \in A$ and some $e' \in \overline{A}$

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either $K ≤_m A$ or
 $K ≤_m \overline{A}$
- Case distinction \varnothing has no code in A, or it has
- **•** By assumption, there is some $e \in A$ and some $e' \in \overline{A}$
- First idea: Define f(x) := e if $x \in K$ and

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either *K* ≤_{*m*} *A* or
 K ≤_{*m*} \overline{A}
- Case distinction \varnothing has no code in A, or it has
- **•** By assumption, there is some $e \in A$ and some $e' \in \overline{A}$
- First idea: Define f(x) := e if $x \in K$ and
- $f(x) := e' \text{ if } x \notin K$

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either $K ≤_m A$ or
 $K ≤_m \overline{A}$
- Case distinction \varnothing has no code in A, or it has
- **•** By assumption, there is some $e \in A$ and some $e' \in \overline{A}$
- First idea: Define f(x) := e if $x \in K$ and
- $f(x) := e' \text{ if } x \notin K$
- Then: $K \leq_m A$

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either $K ≤_m A$ or
 $K ≤_m \overline{A}$
- Case distinction \varnothing has no code in A, or it has
- **•** By assumption, there is some $e \in A$ and some $e' \in \overline{A}$
- First idea: Define f(x) := e if $x \in K$ and
- $f(x) := e' \text{ if } x \notin K$
- Then: $K \leq_m A$: $x \in K \Leftrightarrow f(x) \in A$

- If A is an index set not equal to \emptyset or \mathbb{N} –, then A is incomputable
- First step: it is sufficient to show that either $K ≤_m A$ or
 $K ≤_m \overline{A}$
- Case distinction \varnothing has no code in A, or it has
- **•** By assumption, there is some $e \in A$ and some $e' \in \overline{A}$
- First idea: Define f(x) := e if $x \in K$ and
- $f(x) := e' \text{ if } x \notin K$
- **•** Then: $K \leq_m A$: $x \in K \Leftrightarrow f(x) \in A$
- Alas: f is not computable

Second idea: Define f(x) := e if $x \in K$ and

- Second idea: Define f(x) := e if $x \in K$ and
- and undefined otherwise.

- Second idea: Define f(x) := e if $x \in K$ and
- and undefined otherwise.
- Now f is partially computable.

- Second idea: Define f(x) := e if $x \in K$ and
- and undefined otherwise.
- Now f is partially computable.
- **•** and: $x \in K \Leftrightarrow f(x) \downarrow \in A$

- **Second idea:** Define f(x) := e if $x \in K$ and
- and undefined otherwise.
- Now f is partially computable.
- **•** and: $x \in K \Leftrightarrow f(x) \downarrow \in A$
- **•** But f is not total, so no reduction

- Second idea: Define f(x) := e if $x \in K$ and
- and undefined otherwise.
- Now f is partially computable.
- **•** and: $x \in K \Leftrightarrow f(x) \downarrow \in A$
- \blacksquare But f is not total, so no reduction
- Final idea: $W_{f(x)} := W_e$ if $x \in K$

- **Second idea:** Define f(x) := e if $x \in K$ and
- and undefined otherwise.
- Now f is partially computable.
- **•** and: $x \in K \Leftrightarrow f(x) \downarrow \in A$
- \blacksquare But f is not total, so no reduction
- Final idea: $W_{f(x)} := W_e$ if $x \in K$
- and \varnothing otherwise.

- **Second idea:** Define f(x) := e if $x \in K$ and
- and undefined otherwise.
- Now f is partially computable.
- **•** and: $x \in K \Leftrightarrow f(x) \downarrow \in A$
- **\checkmark** But *f* is not total, so no reduction
- Final idea: $W_{f(x)} := W_e$ if $x \in K$
- and \varnothing otherwise.
- The case that \varnothing has a code in A goes similar (misprint)







🥒 Inf



- 🍠 Fin
- 🥒 Inf
- Cof
- Virus scanner does not exist and *cannot* exist!!!

- 🍠 Fin
- 🥒 Inf
- Cof
- Virus scanner does not exist and *cannot* exist!!!
- and much more



 $=_m is an equivalence relation$



 \blacksquare \equiv_m is an equivalence (reflexive, transitive, symmetric) relation

m-degrees

■ \equiv_m is an equivalence (reflexive, transitive, symmetric) relation , so, we divide it out

m-degrees

- \equiv_m is an equivalence (reflexive, transitive, symmetric) relation , so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq

m-degrees

- \equiv_m is an equivalence (reflexive, transitive, symmetric) relation , so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq
- Notice that it is a well defined notion
- $\blacksquare \equiv_m$ is an equivalence (reflexive, transitive, symmetric) relation, so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq
- Notice that it is a well defined notion
- We always exclude \varnothing and \mathbb{N} as members of *m*-degrees

- $\blacksquare \equiv_m$ is an equivalence (reflexive, transitive, symmetric) relation, so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq
- Notice that it is a well defined notion
- We always exclude \varnothing and \mathbb{N} as members of *m*-degrees
- \bullet < defines a *partial order*

- $\blacksquare \equiv_m$ is an equivalence (reflexive, transitive, symmetric) relation, so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq
- Notice that it is a well defined notion
- We always exclude \varnothing and \mathbb{N} as members of *m*-degrees
- \bullet < defines a *partial order* (refl., trans., antisymm.)

- $\blacksquare \equiv_m$ is an equivalence (reflexive, transitive, symmetric) relation, so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq
- Notice that it is a well defined notion
- We always exclude \varnothing and \mathbb{N} as members of *m*-degrees
- \bullet < defines a *partial order* (refl., trans., antisymm.)
- We call this the ordering of *m*-degrees

- \equiv_m is an equivalence (reflexive, transitive, symmetric) relation , so, we divide it out
- $\mathbf{a}_m := \deg(A)$ with \leq
- Notice that it is a well defined notion
- We always exclude \varnothing and \mathbb{N} as members of *m*-degrees
- \bullet < defines a *partial order* (refl., trans., antisymm.)
- We call this the ordering of *m*-degrees
- \checkmark and denote it \mathcal{D}_m

• There is a minimal element in \mathcal{D}_m :

- **•** There is a minimal element in \mathcal{D}_m :
- If A is decidable, and $B \neq \emptyset$, N, then $A \leq_m B$

- There is a minimal element in \mathcal{D}_m :
- If A is decidable, and $B \neq \emptyset$, N, then $A \leq_m B$
- However, there is no such thing as a maximal *m*-degree as we shall see later

- There is a minimal element in \mathcal{D}_m :
- If A is decidable, and $B \neq \emptyset$, N, then $A \leq_m B$
- However, there is no such thing as a maximal *m*-degree as we shall see later
- Moreover, \mathcal{D}_m does not have such a well-behaved structure as, say, the distributive lattice $\langle \mathcal{E}, \subseteq \rangle$ or the Boolean algebra $\langle \mathcal{P}(X), \subseteq \rangle$

- There is a minimal element in \mathcal{D}_m :
- If A is decidable, and $B \neq \emptyset$, N, then $A \leq_m B$
- However, there is no such thing as a maximal *m*-degree as we shall see later
- Moreover, \mathcal{D}_m does not have such a well-behaved structure as, say, the distributive lattice $\langle \mathcal{E}, \subseteq \rangle$ or the Boolean algebra $\langle \mathcal{P}(X), \subseteq \rangle$
- It is a very interesting and complex structure

- There is a minimal element in \mathcal{D}_m :
- If A is decidable, and $B \neq \emptyset, \mathbb{N}$, then $A \leq_m B$
- However, there is no such thing as a maximal *m*-degree as we shall see later
- Moreover, \mathcal{D}_m does not have such a well-behaved structure as, say, the distributive lattice $\langle \mathcal{E}, \subseteq \rangle$ or the Boolean algebra $\langle \mathcal{P}(X), \subseteq \rangle$
- It is a very interesting and complex (its first order theory is of complexity $\mathbf{0}_m^{\omega}$!) structure

J The structure \mathcal{E}_m does have a maximal element

- **•** The structure \mathcal{E}_m does have a maximal element
- A is c.e. iff $A \leq_m K_0$!

- The structure \mathcal{E}_m does have a maximal element
- A is c.e. iff $A \leq_m K_0$!
- We shall now proof that $deg(K_0)$ (we shall write $0'_m$) is inhabited precisely by all the creative sets

- **•** The structure \mathcal{E}_m does have a maximal element
- A is c.e. iff $A \leq_m K_0$!
- We shall now proof that $deg(K_0)$ (we shall write $0'_m$) is inhabited precisely by all the creative sets
- If C is creative, and $C \leq_m A$ then A is creative too.

- The structure \mathcal{E}_m does have a maximal element
- A is c.e. iff $A \leq_m K_0$!
- We shall now proof that $deg(K_0)$ (we shall write $0'_m$) is inhabited precisely by all the creative sets
- If C is creative, and $C \leq_m A$ then A is creative too. Recall that we now only consider c.e. sets, whence, A is by definition c.e.

- The structure \mathcal{E}_m does have a maximal element
- A is c.e. iff $A \leq_m K_0$!
- We shall now proof that $deg(K_0)$ (we shall write $0'_m$) is inhabited precisely by all the creative sets
- If C is creative, and $C \leq_m A$ then A is creative too. Recall that we now only consider c.e. sets, whence, A is by definition c.e.
- Proof: if C is creative with creative function f and
 $g: C ≤_m A$

- The structure \mathcal{E}_m does have a maximal element
- A is c.e. iff $A \leq_m K_0$!
- We shall now proof that $deg(K_0)$ (we shall write $0'_m$) is inhabited precisely by all the creative sets
- If C is creative, and $C \leq_m A$ then A is creative too. Recall that we now only consider c.e. sets, whence, A is by definition c.e.
- Proof: if C is creative with creative function f and
 $g: C ≤_m A$
- use g⁻¹ to get a set to apply f to, to obtain a new element. Use g again to get the element where is should be.

 \checkmark Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:
- We should find for every c.e. *A* some reduction $g: A \leq_m C$, thus

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:
- We should find for every c.e. A some reduction $g: A \leq_m C$, thus

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:
- We should find for every c.e. *A* some reduction $g: A \leq_m C$, thus

$$\, {\boldsymbol{\mathcal Y}} \in \overline{A} \ \, \Rightarrow g(y) \in \overline{C}$$

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:
- We should find for every c.e. *A* some reduction $g: A \leq_m C$, thus

- Notice, for *f* the creative function: $f(e) \in \overline{C}$ if $W_e = \varnothing$

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:
- We should find for every c.e. *A* some reduction $g: A \leq_m C$, thus

- ▶ Notice, for *f* the creative function: $f(e) \in \overline{C}$ if $W_e = \emptyset$
- How can we make sure that $g(y) \in C$?

- Corollary: there is some a with $\mathbf{0}_m <_m \mathbf{a} < \mathbf{0}'_m$
- Every creative set C is m-complete (John Myhill, 1955)
- Collecting ingredients to find a proof strategy:
- We should find for every c.e. *A* some reduction $g: A \leq_m C$, thus

- ▶ Notice, for *f* the creative function: $f(e) \in \overline{C}$ if $W_e = \emptyset$
- How can we make sure that $g(y) \in C$?

• Well, if
$$W_{g(y)} = \{f(g(y))\}!!!$$

We use the fixed point theorem

Solution We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- ✓ With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

$$W_{g(x,y)} = \{f(x)\} \text{ if } y \in A$$

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

•
$$W_{g(x,y)} = \{f(x)\} \text{ if } y \in A$$

• and \varnothing otherwise

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

•
$$W_{g(x,y)} = \{f(x)\} \text{ if } y \in A$$

- and \varnothing otherwise
- We now find fixed point k(y) with $W_{k(y)} = W_{g(k(y),y)}$

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

•
$$W_{g(x,y)} = \{f(x)\} \text{ if } y \in A$$

- and \varnothing otherwise
- We now find fixed point k(y) with $W_{k(y)} = W_{g(k(y),y)}$
- $(f \circ k)$ is the required reduction:

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

•
$$W_{g(x,y)} = \{f(x)\} \text{ if } y \in A$$

- and \varnothing otherwise
- We now find fixed point k(y) with $W_{k(y)} = W_{g(k(y),y)}$
- $(f \circ k)$ is the required reduction:
Myhill's Theorem

- We use the fixed point theorem: for f(x), we find a fixed point (number) e such that $W_e = W_{f(e)}$
- With parameters: for g(x, y) we find a fixed point (function) k(y) such that $W_{k(y)} = W_{g(k(y),y)}$
- First consider a (total!) recursive g(x, y) such that

•
$$W_{g(x,y)} = \{f(x)\} \text{ if } y \in A$$

- and \varnothing otherwise
- We now find fixed point k(y) with $W_{k(y)} = W_{g(k(y),y)}$
- $(f \circ k)$ is the required reduction: