Advanced Topics in Theoretical Computer Science

Part 3: Recursive Functions (3)

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Exam

Foodle:

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- Recapitulation: Turing machines and Turing computability
- Register machines (LOOP, WHILE, GOTO)
- Recursive functions
- The Church-Turing Thesis
- Computability and (Un-)decidability
- Complexity
- Other computation models: e.g. Büchi Automata, λ-calculus

3. Recursive functions

- Introduction/Motivation
- Primitive recursive functions $\mapsto \mathcal{P}$
- $\mathcal{P} =$ LOOP
- μ-recursive functions $\mapsto F_\mu$
- $F_\mu =$ WHILE
- Summary

Primitive recursive functions

Definition (Primitive recursive functions)

- **Atomic functions:** The functions
  - Null 0
  - Successor $+1$
  - Projection π_i^k $(1 \leq i \leq k)$

  are primitive recursive.
- **Composition:** The functions obtained by composition from primitive recursive functions are primitive recursive.
- **Primitive recursion:** The functions obtained by primitive recursion from primitive recursive functions are primitive recursive.

Notation: $\mathcal{P} =$ The set of all primitive recursive functions

Primitive recursive functions

Primitive recursion

If the functions

$$g : \mathbb{N}^k \to \mathbb{N} \qquad (k \geq 0)$$

$$h : \mathbb{N}^{k+2} \to \mathbb{N}$$

are primitive recursive,

then the function

$$f : \mathbb{N}^{k+1} \to \mathbb{N} \text{ with } \quad \begin{aligned} f(\mathbf{n}, 0) &= g(\mathbf{n}) \\ f(\mathbf{n}, m+1) &= h(\mathbf{n}, m, f(\mathbf{n}, m)) \end{aligned}$$

is also primitive recursive.

Notation without arguments: $f = \mathcal{PR}[g, h]$

Arithmetical functions: definitions

$f(n) = n + c$

$f(n) = n$

$f(n, m) = n + m$

$f(n, m) = n - 1$

$f(n, m) = n - c$

$f(n, m) = n - m$

$f(n, m) = n * m$

$f(n, m) = n^m$

Re-ordering/Omitting/Repeating/Additional arguments

Lemma The set of primitive recursive functions is closed under:

- Re-ordering
- Omitting
- Repeating

of arguments when composing functions.

Lemma. Assume $f : \mathbb{N}^k \to \mathbb{N}$ is primitive recursive.
Then, for every $l \in \mathbb{N}$, the function $f' : \mathbb{N}^k \times \mathbb{N}^l \to \mathbb{N}$ defined for every $\mathbf{n} \in \mathbb{N}^k$ and every $\mathbf{m} \in \mathbb{N}^l$ by:

$$f'(\mathbf{n}, \mathbf{m}) = f(\mathbf{n})$$

is primitive recursive.

Case distinction/ Sums/Products

Lemma (Case distinction is primitive recursive)
If g_i, h_i $(1 \leq i \leq r)$ are primitive recursive functions, and for every n there exists a unique i with $h_i(n) = 0$ then the following function f is primitive recursive:

$$f(n) = \begin{cases} g_1(n) & \text{if } h_1(n) = 0 \\ \dots & \\ g_r(n) & \text{if } h_r(n) = 0 \end{cases}$$

is primitive recursive.

Theorem. If $g : \mathbb{N}^k \times \mathbb{N} \to \mathbb{N}$ is a primitive recursive function then the following functions $f_1, f_2 : \mathbb{N}^k \times \mathbb{N} \to \mathbb{N}$ are also primitive recursive:

$$f_1(\mathbf{n}, m) = \begin{cases} 0 & \text{if } m = 0 \\ \sum_{i<m} g(\mathbf{n}, i) & \text{if } m > 0 \end{cases} \qquad f_2(\mathbf{n}, m) = \begin{cases} 1 & \text{if } m = 0 \\ \prod_{i<m} g(\mathbf{n}, i) & \text{if } m > 0 \end{cases}$$

Bounded μ operator

Definition. Let $g : \mathbb{N}^{k+1} \to \mathbb{N}$ be a function.
The bounded μ operator is defined as follows:

$$\mu_{i<m}\ i\ (g(\mathbf{n}, i) = 0) := \begin{cases} i_0 & \text{if } g(\mathbf{n}, i_0) = 0 \\ & \text{and for all } j < i_0 \quad g(\mathbf{n}, j) \neq 0 \\ 0 & \text{if } g(\mathbf{n}, j) \neq 0 \text{ for all } 0 \leq j < m \\ & \text{or } m = 0 \end{cases}$$

$\mu_{i<m}\ i\ (g(\mathbf{n}, i) = 0)$ is the smallest $i < m$ such that $g(\mathbf{n}, i) = 0$

Theorem. If $g : \mathbb{N}^{k+1} \to \mathbb{N}$ is a primitive recursive function
then the function $f : \mathbb{N}^{k+1} \to \mathbb{N}$ defined below is also primitive recursive.

$$f(\mathbf{n}, m) = \mu_{i<m}\ i\ (g(\mathbf{n}, i) = 0)$$

Prime number functions

Theorem: The following functions are primitive recursive:

(1) The Boolean function $|$: $\mathbb{N} \times \mathbb{N} \to \{0, 1\}$ defined by:

$$|(n, m) = \begin{cases} 1 & \text{if } n \text{ divides } m \\ 0 & \text{otherwise} \end{cases}$$

(2) The Boolean function prime : $\mathbb{N} \to \{0, 1\}$ defined by:

$$\text{prime}(n) = \begin{cases} 1 & \text{if } n \text{ prime} \\ 0 & \text{otherwise} \end{cases}$$

(3) The function $p : \mathbb{N} \to \mathbb{N}$ defined by: $p(n) = p_n$, the n-th prime number.

(4) The function $D : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$ defined by: $D(n, i) = k$ iff k is the power of the i-th prime number in the prime number decomposition of n.

$$D(n, i) = \max(\{j \mid n \bmod p(i)^j = 0\})$$

Prime number functions

Proof:

(1), (2), (3) last time.

Prime number functions

Proof:

(4) $D : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$ defined by: $D(n, i) = k$ iff k is the power of the i-th prime number in the prime number decomposition of n.

$$D(n, i) = \max(\{j \mid n \bmod p(i)^j = 0\})$$

$D(0, i) := 0;$

$D(n, i) = \min(\{j \leq n \mid \quad |(p(i)^{j+1}, n) = 0\})$

$D(n, i) = \mu_{j \leq n}\, j\ (|(p(i)^{j+1}, n) = 0)$

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3. Recursive functions

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Goal

Show that $\mathcal{P} = \mathsf{LOOP}$

Idea:

To show that $\mathcal{P} \supseteq \mathsf{LOOP}$ we have to show that every LOOP computable function can be expressed as a primitive recursive function.

For this, we will encode the contents of arbitrarily many registers in one natural number (used as input for this primitive recursive function).

For this encoding we will use Gödelisation. We will need to show that Gödelisation is primitive recursive.

To show that $\mathcal{P} \subseteq \mathsf{LOOP}$ we have to show that:
– all atomic primitive recursive functions are LOOP computable, and
– LOOP is closed under composition of functions and primitive recursion.

Gödelisation

To show: Gödelisation is primitive recursive

Informally:

- Coding number sequences as a number
- Corresponding decoding function (projection)

are primitive recursive

Gödelisation

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Informally:

- Coding number sequences as a number
- Corresponding decoding function (projection)

are primitiv recursive

More precise formulation:

There exist primitive recursive functions

$$K^r : \mathbb{N}^r \to \mathbb{N} \qquad (r \geq 1)$$
$$D_i : \mathbb{N} \to \mathbb{N} \qquad (1 \leq i \leq r)$$

with:

$$D_i(K^r(n_1, \ldots, n_r)) = n_i$$

Gödelisation

To show: Gödelisation is primitive recursive

Informally:

- Coding number sequences as a number
- Corresponding decoding function (projection)

are primitive recursive

Recall:

Gödelisation: Coding number sequences as a number

Bijection between $\mathbb{N}^r$ and $\mathbb{N}$: $K^r : \mathbb{N}^r \rightarrow \mathbb{N}$, defined by:

$$K^r(n_1, \ldots, n_r) = \prod_{i=1}^{r} p(i)^{n_i}.$$

Decoding: The inverses $D_i : \mathbb{N} \rightarrow \mathbb{N}$ of K^r defined by $D_i(n) = D(n, i)$

Gödelisation

Bijection between $\mathbb{N}^r$ and $\mathbb{N}$: $K^r : \mathbb{N}^r \to \mathbb{N}$, defined by:

$$K^r(n_1, \ldots, n_r) = \prod_{i=1}^{r} p(i)^{n_i}.$$

$D_i : \mathbb{N} \to \mathbb{N}$, $1 \leq i \leq r$, defined by $D_i(n) = D(n, i)$

Theorem. K^r and $D_1, \ldots, D_r$ are primitive recursive.

Gödelisation

Bijection between $\mathbb{N}^r$ and $\mathbb{N}$: $K^r : \mathbb{N}^r \to \mathbb{N}$, defined by:

$$K^r(n_1, \dots, n_r) = \prod_{i=1}^{r} p(i)^{n_i}.$$

$D_i : \mathbb{N} \to \mathbb{N}$, $1 \leq i \leq r$, defined by $D_i(n) = D(n, i)$

Theorem. K^r and $D_1, \dots, D_r$ are primitive recursive.

Lemma.
(1) $D_i(K^r(n_1, \dots, n_r)) = n_i \quad$ for all $1 \leq i \leq r$.
(2) $K^r(n_1, \dots, n_r) = K^{r+1}(n_1, \dots, n_r, 0)$

In general, $D_i(K^r(n_1, \dots, n_r)) = 0$ if $i > r$.

Gödelisation

Notation:

$$\begin{aligned} K^r(n_1, \ldots, n_r) &= \langle n_1, \ldots, n_r \rangle \\ D_i(n) &= (n)_i \end{aligned}$$

For $r = 0$:

$\langle\rangle = 1$

$(\langle\rangle)_i = 0$

Gödelisation: Applications

Theorem (Simultaneous Recursion)

If

$$\begin{aligned}
f_1(\mathbf{n}, 0) &= g_1(\mathbf{n}) \\
&\dots \\
f_r(\mathbf{n}, 0) &= g_r(\mathbf{n}) \\
f_1(\mathbf{n}, m+1) &= h_1(\mathbf{n}, m, f_1(\mathbf{n}, m), \dots, f_r(\mathbf{n}, m)) \\
&\dots \\
f_r(\mathbf{n}, m+1) &= h_r(\mathbf{n}, m, f_1(\mathbf{n}, m), \dots, f_r(\mathbf{n}, m))
\end{aligned}$$

and if $g_1, \dots, g_r, h_1, \dots, h_r$ are primitive recursive

then $f_1, \dots, f_r$ are primitive recursive.

Example

Let f_1 and f_2 be defined by simultaneous recursion as follows:

$$\begin{aligned} f_1(0) &= 0 \\ f_2(0) &= 1 \end{aligned}$$

$$\begin{aligned} f_1(n+1) &= f_2(n) \\ f_2(n+1) &= f_1(n) + f_2(n) \end{aligned}$$

Example

Let f_1 and f_2 be defined by simultaneous recursion as follows:

$$\begin{aligned} f_1(0) &= 0 & g_1 &= 0 \\ f_2(0) &= 1 & g_2 &= 1 \end{aligned}$$

$$\begin{aligned} f_1(n+1) &= f_2(n) & h_1(n, f_1(n), f_2(n)) &= f_2(n) & h_1 &= \pi^3_3 \\ f_2(n+1) &= f_1(n) + f_2(n) & h_2(n, f_1(n), f_2(n)) &= f_1(n) + f_2(n) & h_2 &= + \circ (\pi^3_2, \pi^3_3) \end{aligned}$$

Gödelisation: Applications

Theorem (Simultaneous Recursion)

If

$$\begin{aligned} f_1(\mathbf{n}, 0) &= g_1(\mathbf{n}) \\ &\dots \\ f_r(\mathbf{n}, 0) &= g_r(\mathbf{n}) \\ f_1(\mathbf{n}, m+1) &= h_1(\mathbf{n}, m, f_1(\mathbf{n}, m), \dots, f_r(\mathbf{n}, m)) \\ &\dots \\ f_r(\mathbf{n}, m+1) &= h_r(\mathbf{n}, m, f_1(\mathbf{n}, m), \dots, f_r(\mathbf{n}, m)) \end{aligned}$$

and if $g_1, \dots, g_r, h_1, \dots, h_r$ are primitive recursive

then $f_1, \dots, f_r$ are primitive recursive.

Gödelisation: Applications

Proof: We define a new function f by:

$$f(\mathbf{n}, m) = \langle f_1(\mathbf{n}, m), \dots, f_r(\mathbf{n}, m) \rangle$$

f can be computed by primitive recursion as follows:

$$\begin{aligned} f(\mathbf{n}, 0) &= \langle g_1(\mathbf{n}), \dots, g_r(\mathbf{n}) \rangle \\ f(\mathbf{n}, m+1) &= \langle h_1(\mathbf{n}, m, (f(\mathbf{n}, m))_1, \dots, (f(\mathbf{n}, m))_r), \dots, \\ &\quad\; h_r(\mathbf{n}, m, (f(\mathbf{n}, m))_1, \dots, (f(\mathbf{n}, m))_r) \rangle \end{aligned}$$

$K^r \circ (g_1, \dots, g_r)$ and $K^r \circ (h_1, \dots, h_r)$ are primitive recursive.

For all $1 \leq i \leq r$, $f_i(\mathbf{n}, m) = D_i(f(\mathbf{n}, m))$.

Since $f_i = D_i \circ f$ is primitive recursive, it follows that f_i is primitive recursive for all $1 \leq i \leq r$.

Goal

Show that $\mathcal{P} = \text{LOOP}$

Idea:

To show that $\mathcal{P} \supseteq \text{LOOP}$ we have to show that every LOOP computable function can be expressed as a primitive recursive function.

For this, we will encode the contents of arbitrarily many registers in one natural number (used as input for this primitive recursive function).

For this encoding we use Gödelisation. We showed that Gödelisation is primitive recursive.

To show that $\mathcal{P} \subseteq \text{LOOP}$ we have to show that:
– all atomic primitive recursive functions are LOOP computable, and
– LOOP is closed under composition of functions and primitive recursion.

$\mathcal{P} = \textbf{LOOP}$

Theorem ($\mathcal{P}$ = LOOP). The set of all LOOP computable functions is equal to the set of all primitive recursive functions

Proof (Idea)

1. $\mathcal{P} \subseteq$ LOOP

$\mathcal{P}$ = LOOP

Theorem ($\mathcal{P}$ = LOOP). The set of all LOOP computable functions is equal to the set of all primitive recursive functions

Proof (Idea)

1. $\mathcal{P} \subseteq$ LOOP

1a: We show that all atomic primitive recursive functions are LOOP computable

1b: We show that LOOP is closed under composition of functions

1c: We show that LOOP is closed under primitive recursion

$\mathcal{P}$ = LOOP

Theorem ($\mathcal{P}$ = LOOP). The set of all LOOP computable functions is equal to the set of all primitive recursive functions

Proof (Idea)

1. $\mathcal{P} \subseteq$ LOOP

1a: All atomic primitive recursive functions are LOOP computable

$$\begin{array}{rll} 0: & \mathtt{x}_1 := \mathtt{x}_1 - 1 & //NOP \\ +1: & \mathtt{x}_2 := \mathtt{x}_1 + 1 & \\ \pi^k_j & \mathtt{x}_{\mathtt{k}+1} := \mathtt{x}_\mathtt{j} & \end{array}$$

$\mathcal{P}$ = LOOP

Proof (ctd) 1b: LOOP is closed under composition of functions

Let $f : \mathbb{N}^k \to \mathbb{N}$ with $f(\mathbf{n}) = h(g_1(\mathbf{n}), \dots, g_r(\mathbf{n}))$

Assume that:

- P_h computes h
- P_{g_j} computes $g_j \quad (1 \leq j \leq r)$

Idea: f is computed by the program P_f:

$$P'_{g_1}; \dots; P'_{g_r}; P'_h$$

where P'_{g_i} differs from P_{g_i} (and P'_h from P_h) only up to the fact that registers have been renamed/the contents stored in them copied.

$\mathcal{P}$ = LOOP

Proof (ctd) 1b: LOOP is closed under composition of functions

Let $f : \mathbb{N}^k \to \mathbb{N}$ with $f(\mathbf{n}) = h(g_1(\mathbf{n}), \dots, g_r(\mathbf{n}))$

Assume that:

- P_h computes h
- P_{g_j} computes g_j $(1 \leq j \leq r)$

More precisely: P'_{g_i}: obtained from P_{g_i} by renaming register x_{k+i} to x_{k+r+i}.
$\mapsto$ keep free registers $x_{k+1}, \dots, x_{k+r}$ for writing result of $P_{g_1}, \dots, P_{g_r}$

P'_h: obtained from P_h by renaming x_j to x_{k+j}.

$$
\begin{aligned}
P_f : \quad & P'_{g_1}; x_{k+1} := x_{k+r+1}; x_{k+r+1} := 0; \dots \\
& P'_{g_r}; x_{k+r} := x_{k+r+1}; x_{k+r+1} := 0; \\
& P'_h; x_{k+1} := x_{k+r+1}; x_{k+2} := 0; \dots; x_{k+r+1} := 0
\end{aligned}
$$

$\mathcal{P}$ = LOOP

Proof (ctd) 1c: LOOP is closed under primitive recursion

Assume that $f : \mathbb{N}^{k+1} \to \mathbb{N}$ is such that:

$$f(\mathbf{n}, 0) = g(\mathbf{n})$$

$$f(\mathbf{n}, m+1) = h(\mathbf{n}, m, f(\mathbf{n}, m))$$

Then f is computed by the following LOOP Program:

$x_{\text{store}_\text{m}} := x_{k+1}$; // Number of loops (m)
$x_{k+1} := 0$; //Actual value of m (at the beginning 0)
P'_g; // Computes $f(n, 0)$; result in x_{k+2}
loop $x_{\text{store}_\text{m}}$ do
  P_h; // Computes $f(n, x_{k+1}+1) = h(n, m, f(n, m))$
  $x_{k+2} := x_{k+2+1}$; // $x_{k+2} = f(n, x_{k+1}+1)$
  $x_{k+2+1} := 0$;
  $x_{k+1} := x_{k+1} + 1$ // $m = m+1$
end;
$x_{\text{store}_\text{m}} := 0$

$\mathcal{P}$ = **LOOP**

Proof (ctd) 1c: LOOP is closed under primitive recursion

Assume that $f : \mathbb{N}^{k+1} \to \mathbb{N}$ is such that:

$$f(\mathbf{n}, 0) = g(\mathbf{n})$$

$$f(\mathbf{n}, m+1) = h(\mathbf{n}, m, f(\mathbf{n}, m))$$

Then f is computed by the following LOOP Program:

$x_{\text{store}_m} := x_{k+1}$; // Number of loops (m)
$x_{k+1} := 0$; //Actual value of m (at the beginning 0)
P'_g; // Computes $f(n, 0)$; result in x_{k+2}
loop x_{store_m} do
  P_h;
  $x_{k+2} := x_{k+2+1}$;
  $x_{k+2+1} := 0$;
  $x_{k+1} := x_{k+1} + 1$
end;
$x_{\text{store}_m} := 0$

where P'_g differs from P_g only in the fact that some registers have been renamed (e.g. output in x_{k+2}, not in x_{k+1})

$\mathcal{P}$ = LOOP

Theorem ($\mathcal{P}$ = LOOP). The set of all LOOP computable functions is equal to the set of all primitive recursive functions

Proof (Idea)

2. LOOP $\subseteq \mathcal{P}$

Let P be a LOOP program which:

- uses registers $x_1, \ldots, x_l$
- has m loop instructions

We construct a primitive recursive function f_P which "simulates" P

$$f_P(\langle n_1, \ldots, n_l, h_1, \ldots, h_m \rangle) = \langle n'_1, \ldots, n'_l, h_1, \ldots, h_m \rangle$$

if and only if:

P started with n_i in register x_i terminates with n'_i in x_i $(1 \leq i \leq l)$.

In h_j it is "recorded" how long loop j should still run.

$\mathcal{P}$ = LOOP

Proof (ctd)

At the beginning and at the end of the simulation of P we have

$$h_1 = 0, \ldots, h_m = 0.$$

Assume that we can construct a primitive recursive function f_P which "simulates" P,
i.e. $f_P(\langle n_1, \ldots, n_l, h_1, \ldots, h_m \rangle) = \langle n'_1, \ldots, n'_l, h_1, \ldots, h_m \rangle$
if and only if:

P started with n_i in register x_i terminates with n'_i in x_i $(1 \leq i \leq l)$.

The function computed by the LOOP program P is then primitive recursive, since:

$$g(n_1, \ldots, n_l) = g(n_1, \ldots, n_k, 0, \ldots, 0) = (f_P(\langle n_1, \ldots, n_l, 0, 0, \ldots \rangle))_{k+1}$$

(the input in registers $x_1, \ldots, x_k$, all other registers contain 0, output in register x_{k+1}

$\mathcal{P}$ = LOOP

Proof (ctd) **Construction of f_P:**

2a: P is $x_i := x_i + 1$

$$f_P(n) = \langle (n)_1, \ldots, (n)_{i-1}, (n)_i + 1, (n)_{i+1}, \ldots \rangle = n * p(i)$$

P is $x_i := x_i - 1$

$$f_P(n) = \langle (n)_1, \ldots, (n)_{i-1}, (n)_i - 1, (n)_{i+1}, \ldots \rangle$$

$$f_P(n) = \begin{cases} n & D(n,i) = 0 \\ n\ DIV\ p(i) & \text{otherwise} \end{cases}$$

$\mathcal{P}$ = **LOOP**

Proof (ctd) **Construction of f_P:**

2a: P is $x_i := x_i + 1$

$$f_P(n) = \langle (n)_1, \ldots, (n)_{i-1}, (n)_i + 1, (n)_{i+1}, \ldots \rangle$$

P is $x_i := x_i - 1$

$$f_P(n) = \langle (n)_1, \ldots, (n)_{i-1}, (n)_i - 1, (n)_{i+1}, \ldots \rangle$$

2b: P is $P_1; P_2$

$$f_P = f_{P_2} \circ f_{P_1} \qquad i.e.\ f_P(n) = f_{P_2}(f_{P_1}(n))$$

$\mathcal{P} = \textbf{LOOP}$

Proof (ctd) **Construction of f_P:**

2c: P is loop x_i do P_1 end

Let f_{P_1} be the p.r. function which computes what P_1 computes.

Initialize the j-th loop:

$$f_1(n) = \big\langle (n)_1, \ldots, (n)_l, (n)_{l+1}, \ldots (n)_{l+j-1}, (n)_i, (n)_{l+j+1}, \ldots \big\rangle$$

Let the j-th loop run:

$$f_2(n) = \begin{cases} n & \text{if } (n)_{l+j} = 0 \\ f_{P_1}(f_2(\big\langle \ldots, (n)_{l+j} - 1, \ldots \big\rangle)) & \text{otherwise} \end{cases}$$

Then:

$$f_P(n) = f_2(f_1(n)) = (f_2 \circ f_1)(n)$$

$\mathcal{P}$ = LOOP

Proof (ctd) **Construction of f_P:**

2c: P is loop x_i do P_1 end

Let f_{P_1} be the p.r. function which computes what P_1 computes.

Initialize the j-th loop:

$$f_1(n) = \left\langle (n)_1, \ldots, (n)_l, (n)_{l+1}, \ldots (n)_{l+j-1}, (n)_i, (n)_{l+j+1}, \ldots \right\rangle$$

$f_1(n) = n * p(l+j)^{(n)_i}$. if $(n)_{l+j} = 0$ before the loop is executed

Let the j-th loop run:

$$f_2(n) = \begin{cases} n & \text{if } (n)_{l+j} = 0 \\ f_{P_1}(f_2(n \; DIV \; p(l+j))) & \text{otherwise} \end{cases}$$

Then:

$$f_P = f_2 \circ f_1$$

$\mathcal{P} = \textbf{LOOP}$

Proof (ctd) We show that f_2 is primitive recursive.

Let $F : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$ be defined by:

$F(n, 0) = n$

$F(n, m + 1) = f_{P_1}(F(n, m))$

Then $F \in \mathcal{P}$.

It can be checked that $f_2(n) = F(n, D(n, l + j))$. Therefore, $f_2 \in \mathcal{P}$.

Since f_1, f_2 are primitive recursive, so is $f_P = f_2 \circ f_1$.

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Next lecture

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