



INDUCTIVE DEFINITION

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OUTLINE

- Judgements
- Inference Rules
- Inductive Definition
- Derivation
- Rule Induction

LANGUAGE AND META-LANGUAGE

- **Language** is the target programming language, e.g., Java, Python, ML.
 - Has its own identifiers, variables, etc.
- **Meta-language** is the language in which to describe the target language.
 - E.g. *Language L1 is more concise than language L2* (this is a statement in a meta-language, that's neither L1 or L2).

META-VARIABLES

- A symbol in a meta-language that is used to describe some element in an object (target) language
 - E.g., Let **a** and **b** be two sentences of a language \mathcal{L}
 - E.g., Let **n** be a number, **d** be a digit and **s** be a sign in the language of *numerals*
 - 435, 535.23, -3847 are all numbers in the language of numerals
 - meta-variable doesn't appear in the language itself.
- **Meta-** is a prefix used to indicate a concept, which is an abstraction from another concept, used to complete or add to the latter.
- Similar use in “meta-data”, “meta-theory”, etc.
 - The syntax, semantics, etc. about a PL (e.g., Java) is the *meta-theory* about that language

JUDGEMENTS

- A *judgement* is an *assertion* (in the meta-language) about one or more syntactic objects.

Judgement

n nat

$n = n_1 + n_2$

τ type

$e:\tau$

$e \Downarrow v$

Meaning

(n is a natural number)

(n is the sum of n_1 and n_2)

(τ is a type)

(expression e has type τ)

(expression e has value v)

- “ n nat” can also be written as “ n isa nat”, “ n is a natural num”, etc. as long as it’s consistent and understandable.

JUDGEMENTS (II)

- A judgement states one or more *syntactic objects* have a *property* or have a *relation* among one another.
- The property or the relation itself is called *predicate*.
 - E.g., $n \text{ nat}$ (this judgement involves one object n)
- The abstract structure (schema) of a judgement is called *judgement form*.
 - E.g., $n \text{ nat}$.
- The judgement that a particular object or objects having that property is an *instance* of a judgement form.
 - E.g., 5 nat , $\text{succ}(n) \text{ nat}$ are all judgements
- W.L.O.G., we use “judgement” to mean the instance of judgement form usually.

INFERENCE RULES

- An inductive definition of a judgement form consists of a collection of rules of the form:

$$\frac{J_1 \quad \dots \quad J_k}{J}$$

The diagram illustrates an inference rule. It shows a horizontal line with J_1 , \dots , and J_k above it, and J below it. An orange arrow points from the word "premises" to the sequence $J_1 \dots J_k$. Another orange arrow points from the word "conclusion" to J .

- To show J , it is sufficient to show J_1, \dots, J_k .
- A rule without premises is called an *axiom*;
- Otherwise, it's called a *proper rule*.

INDUCTIVE DEFINITION

- Definition of judgement form *n nat*:

$$\frac{}{\text{zero } \text{nat}} \qquad \frac{n \text{ nat}}{\text{succ}(n) \text{ nat}}$$

- Definition of judgement form *t tree*:

$$\frac{}{\text{empty tree}} \qquad \frac{t_1 \text{ tree} \quad t_2 \text{ tree}}{\text{node}(t_1; t_2) \text{ tree}}$$

Axioms!

Proper Rules!

QUIZ: JUDGEMENT AND JUDGEMENT FORM

- Please circle and indicate all the **judgement forms** and **judgements** you can find in the following inductive definition:

Definition of **t tree**:

$$\frac{}{\text{empty tree}} \qquad \frac{t_1 \text{ tree} \quad t_2 \text{ tree}}{\text{node}(t_1; t_2) \text{ tree}}$$

DERIVATION

- To show an inductively defined judgement holds \rightarrow exhibit a derivation of the judgement.
- A derivation is an *evidence* for the validity of the defined judgement.
- Derivation of a judgement is the finite composition of rules starting from *axioms* and ending at *that judgement*.
- Usually a tree structure
 - In compiler, derivation of grammar in the form of a *parse tree*.

DERIVATION (II)

- Derivation of judgement $\text{succ}(\text{succ}(\text{succ}(\text{zero}))) \text{ nat}$:

$$\frac{\frac{\frac{\frac{}{\text{zero nat}} \text{(Z)}}{\text{succ}(\text{zero}) nat} \text{(S)}}{\text{succ}(\text{succ}(\text{zero})) nat} \text{(S)}}{\text{succ}(\text{succ}(\text{succ}(\text{zero}))) nat} \text{(S)}$$

$$\frac{\frac{}{\text{zero nat}} \text{(Z)}}{\text{succ}(n) nat} \text{(S)}$$

DERIVATION (II)

- Derivation of **node(node(empty, empty), empty) tree**:

$$\frac{}{\text{empty tree}}^{(e)}$$

$$\frac{t_1 \text{ tree} \quad t_2 \text{ tree}}{\text{node}(t_1; t_2) \text{ tree}}^{(t)}$$

$$\frac{\frac{}{\text{empty tree}}^{(e)} \quad \frac{}{\text{empty tree}}^{(e)}}{\text{node}(\text{empty}; \text{empty}) \text{ tree}}^{(t)} \quad \frac{}{\text{empty tree}}^{(e)}$$

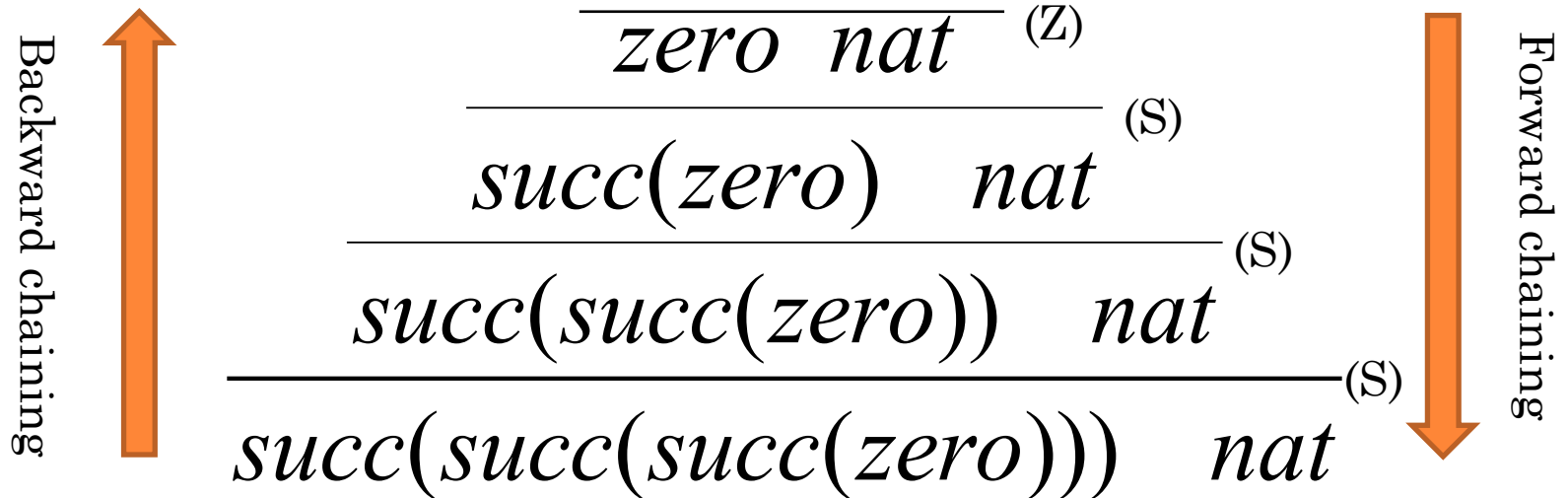
$$\frac{\text{node}(\text{empty}; \text{empty}) \text{ tree} \quad \text{empty tree}}{\text{node}(\text{node}(\text{empty}; \text{empty}); \text{empty}) \text{ tree}}^{(t)}$$

TYPES OF DERIVATION

- Forward chaining (bottom-up):
 - Starting from axioms, work up to the conclusion
- Backward chaining (top-down):
 - Start from the conclusion, work backwards toward axioms
- Note the terms bottom-up and top-down are exactly the **opposite** of the derivation tree we presented.

TYPE OF DERIVATION

- Derivation of judgement $\text{succ}(\text{succ}(\text{succ}(\text{zero}))) \text{ nat}$:



QUIZ: DERIVATION

Given the inductive definition of judgment form:

$\boxed{e \text{ exp}}$ (e is an expression)

$$\frac{}{0,1,2,\dots,\infty \text{ exp}} \text{ (num-e)}$$

$$\frac{e_1 \text{ exp} \quad e_2 \text{ exp}}{e_1 + e_2 \text{ exp}} \text{ (add-e)}$$

$$\frac{e_1 \text{ exp} \quad e_2 \text{ exp}}{e_1 - e_2 \text{ exp}} \text{ (sub-e)}$$

Write down the derivation (tree) of:

13-24+5-6 exp

make sure to include the rule labels

DEDUCTIVE SYSTEMS

- A deductive system has 2 parts:
 - Definition of one or more *judgement forms*
 - A collection of *inference rules* about these judgement forms
- We have just introduced two deductive systems: *nat* and *tree*.
- A *programming language* can be represented by a deductive system, of course with many judgement forms and inference rules!

RULE INDUCTION (I)

- Reason about rules under an inductive definition (or within a deductive system)
- Principle of rule induction:
 - To show property P holds of a judgement form J whenever J is derivable, it is enough to show that P *is closed under*, or *respects*, all the rules defining J .
 - Write $P(J)$ to mean property P holds for J .
 - We say P respects the rule

$$\frac{J_1 \dots J_k}{J_{k+1}}$$

if $P(J_{k+1})$ holds whenever $P(J_1), \dots, P(J_k)$ hold.

- $P(J_1), \dots, P(J_k)$ are *inductive hypothesis*.
- $P(J_{k+1})$ is *inductive conclusion*.

RULE INDUCTION (II)

- For the judgement form $n \text{ nat}$, to show $P(n \text{ nat})$, it is sufficient to show:
 1. $P(\text{zero nat})$.
 2. For every n , if $P(n \text{ nat})$, then $P(\text{succ}(n) \text{ nat})$.
- Looks familiar?
- This is just a generalized version of *mathematical induction*.
- Step 1 is called the *basis*; step 2 is called the *induction step*.
- Similar induction can be applied on $\text{node}(t_1, t_2)$ tree \rightarrow “*tree induction*”.



PROOF BY INDUCTION

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OUTLINE

- Proof Principles
- Natural Numbers
- List
- Proof Structure

PROOF PRINCIPLE (RULE INDUCTION)

- Recall that...
- To show every derivable judgement has some property P, show for every rule in the deductive system:

$$\frac{J_1 \dots J_n}{J} [name]$$

- If J_1, \dots, J_n have property P then J has property P.

EXAMPLE (NATURAL NUMBERS)

- Given a property P , we know that P is true for all natural numbers, if we can prove:
 - P holds unconditionally for Z . Corresponds to rule Z :

$$\frac{}{Z \text{ nat}} Z$$

- Assuming P holds for n , then P holds for $(S \ n)$. Corresponds to rule S :

$$\frac{n \text{ nat}}{S \ n \text{ nat}} S$$

- Also called “induction on the structure of natural numbers”.

NATURAL NUMBERS

- Natural numbers:

$$\frac{}{Z \text{ nat}} Z$$

$$\frac{n \text{ nat}}{S n \text{ nat}} S$$

- Addition:

- Judgement: $\text{add } n1 \ n2 \ n3$

$$\frac{}{\text{add } Z \ n \ n} \text{add}Z$$

$$\frac{\text{add } n1 \ n2 \ n3}{\text{add } (S \ n1) \ n2 \ (S \ n3)} \text{add}S$$

Theorem 1: For all $n1, n2$, there exists $n3$ such that $\text{add } n1 \ n2 \ n3$.
(if $n1 \text{ nat}$, $n2 \text{ nat}$, then there exists $n3 \text{ nat}$ such that $\text{add } n1 \ n2 \ n3$)

Proof: **By induction on the derivation of $n \text{ nat}$.**

Case: $\frac{\text{---}}{Z \text{ nat}} Z$

Need to prove $\text{add } n1 \ n2 \ n3$ where $n1 = Z$

- (1) $\text{add } Z \ n2 \ n2$ (by addZ , and let $n=n2$)
- (2) $\text{add } n1 \ n2 \ n3$ (by letting $n1=Z$, $n3=n2$)

Renaming!

(Case proved)

Case: $\frac{n \text{ nat}}{S \ n \text{ nat}} S$

Need to prove $\text{add } n1 \ n2 \ n3$ where $n1 = (S \ n)$

- (1) $\text{add } n \ n2 \ n3'$ (by I.H. and let $n = n1$, $n3'=n3$)
- (2) $\text{add } (S \ n) \ n2 \ (S \ n3')$ (by (1), addS , and
let $(S \ n) = n1$, $(S \ n3')=n3$)

(Case proved) QED.

$$\frac{\frac{\text{---}}{\text{add } Z \ n \ n} \text{addZ}}{\text{add } (S \ n1) \ n2 \ (S \ n3)} \text{addS}$$

EVEN/ODD NUMBERS

○ Judgements:

- $\text{even } n$ “ n is an even number”
- $\text{odd } n$ “ n is an odd number”

$$\frac{}{\text{even } Z} \text{even}Z \qquad \frac{\text{odd } n}{\text{even } (S n)} \text{even}S$$

$$\frac{\text{even } n}{\text{odd } (S n)} \text{odd}S$$

Theorem 2: If n nat, then either even n or odd n .

Proof: **By induction on the derivation of n nat.**

Case:
$$\frac{}{Z \text{ nat}} Z$$

even Z (By rule evenZ)

Case:
$$\frac{n \text{ nat}}{S n \text{ nat}} S$$

(1) even n or (2) odd n (By I.H.)

Need to prove: even $(S n)$ or odd $(S n)$

Assuming (1):

odd $(S n)$ (By (1) and rule oddS)

Assuming (2):

even $(S n)$ (By (2) and rule evenS)

QED.

$$\frac{}{\text{even } Z} \text{evenZ}$$

$$\frac{\text{odd } n}{\text{even } (S n)} \text{evenS}$$

$$\frac{\text{even } n}{\text{odd } (S n)} \text{oddS}$$

EVEN/ODD NUMBER (ALT. DEFINITION)

$$\frac{}{\text{even2 } Z} \text{even2}Z$$

$$\frac{\text{even2 } n}{\text{even2 } (S (S n))} \text{even2}S$$

$$\frac{}{\text{odd2 } (S Z)} \text{odd2}Z$$

$$\frac{\text{odd2 } n}{\text{odd2 } (S (S n))} \text{odd2}S$$

Theorem 3: If $\text{even2 } n$, then $\text{even } n$.

Proof: By induction on the derivation of $\text{even2 } n$.

Case:
$$\frac{}{\text{even2 } Z} \text{even2Z}$$

$\text{even } Z$

(by rule evenZ)

Case:
$$\frac{\text{even2 } n}{\text{even2 } (S (S n))} \text{even2S}$$

(1) $\text{even } n$

(by I.H.)

Need to prove: $\text{even } (S (S n))$

(2) $\text{odd } (S n)$

(by (1), oddS)

(3) $\text{even } (S (S n))$

(by (2), evenS)

QED.

$$\frac{\frac{\frac{}{\text{even } Z} \text{evenZ}}{\text{odd } n} \text{evenS}}{\text{odd } (S n)} \text{oddS}$$

LIST OF NATURAL NUMBERS

- Judgement Form:

- $l \text{ list}$ “ l is a list”

$$\frac{}{nil \text{ list}} nil$$

$$\frac{n \text{ nat} \quad l \text{ list}}{cons(n, l) \text{ list}} cons$$

- Cons stands for “CONcatenateS”
- Means concatenation of a *head* and a *tail* of a list.
- In $cons(n, l)$, n is the head and l is the tail.
- $cons(1, cons(2, cons(3, nil))) = 1::2::3::nil = [1,2,3]$

Lemma 1: $\text{cons}((S\ Z), \text{cons}(Z, \text{nil}))$ is a list.

Proof: By giving a derivation of $\text{cons}((S\ Z), \text{cons}(Z, \text{nil}))$ list.

$$\begin{array}{c} \begin{array}{ccc} Z\ \text{nat} & (\text{by } Z) & \\ \hline (S\ Z)\ \text{nat} & & \end{array} & \begin{array}{ccc} Z\ \text{nat} & (\text{by } Z) & \text{nil list} & (\text{by nil}) \\ \hline \text{cons}(Z, \text{nil})\ \text{list} & & \end{array} \\ \hline \text{cons}((S\ Z), \text{cons}(Z, \text{nil}))\ \text{list} \end{array}$$

LIST - LEN

- Judgment Form: $\text{len } l \text{ } n$.
 - “the length of l is n ”.

$$\frac{}{\text{len nil } Z} \text{len} - \text{nil}$$

$$\frac{\text{len } l \text{ } n}{\text{len cons}(n_1, l) (S \text{ } n)} \text{len} - \text{cons}$$

LIST - APPEND

- Judgment Form: $\text{append } l_1 \text{ } n \text{ } l_2$.
 - “ l_2 is the result of appending n to l_1 ”.

$$\frac{}{\text{append nil } n \text{ cons}(n, \text{nil})} \text{append} - \text{nil}$$

$$\frac{\text{append } l \text{ } n_2 \text{ } l_1}{\text{append cons}(n_1, l) \text{ } n_2 \text{ cons}(n_1, l_1)} \text{append} - \text{cons}$$

LIST - REVERSE

- Judgment Form: $\text{reverse } l_1 \ l_2$.
 - “ l_2 is the reversed form of list l_1 ”.

$$\frac{}{\text{reverse nil nil}} \text{rev} - \text{nil}$$

$$\frac{\text{reverse } l_1 \ l_2 \quad \text{append } l_2 \ n \ l_2'}{\text{reverse cons}(n, l_1) \ l_2'} \text{rev} - \text{cons}$$

THEOREM: LENGTH OF REVERSED LIST

Theorem 4: If $\text{len } l = n$, and $\text{reverse } l = l'$, then $\text{len } l' = n$.

Proof: To prove this theorem, we first prove the following lemma:

Lemma 2: If $\text{len } l = n$, and $\text{append } l \ n_1 = l'$, then $\text{len } l' = (n + 1)$.

$$\frac{}{len\ nil\ Z} len - nil$$

$$\frac{len\ l\ n}{len\ cons(n_1, l)\ (S\ n)} len - cons$$

Lemma 2: If $len\ l\ n$, and $append\ l\ n_1\ l'$, then $len\ l'\ (S\ n)$.

Proof: **By induction on the derivation of append.**

Case:

$$\frac{}{append\ nil\ n\ cons(n, nil)} append - nil$$

Need to prove: if $len\ nil\ n$, and $append\ nil\ n_1\ l'$, then $len\ l'\ (S\ n)$

- (1) $len\ nil\ Z$ (By $len-Z$)
- (2) $append\ nil\ n_1\ cons(n_1, nil)$ (By $append-nil$ and let $n = n_1$)
- (3) $len\ cons(n_1, nil)\ (S\ Z)$ (By $len-cons$ and (1) and let $l' = cons(n_1, nil)$ and $n = Z$)

$$\frac{}{\text{len nil } Z} \text{len} - \text{nil}$$

$$\frac{\text{len l n}}{\text{len cons}(n_1, l) (S n)} \text{len} - \text{cons}$$

Case:
$$\frac{\text{append l } n_2 \text{ l}_1}{\text{append cons}(n_1, l) \text{ } n_2 \text{ cons}(n_1, l_1)} \text{append} - \text{cons}$$

- (1) len l n and $\text{append l } n_2 \text{ l}_1$ (By assumption)
- (2) $\text{len l}_1 (S n)$ (By (1) and I.H.)

Need to prove: if $\text{len cons}(n_1, l) n'$ and $\text{append cons}(n_1, l) n_2 \text{ cons}(n_1, l_1)$, then $\text{len cons}(n_1, l_1) (S n')$

- (3) $\text{len cons}(n_1, l) (S n)$ (By (1) and len-cons)
- (4) $\text{len cons}(n_1, l_1) (S (S n))$ (By (2) and len-cons and let $n' = (s n)$)

QED.

Now continue to prove Theorem 4.

Proof: **By induction on the derivation of len.**

Case:
$$\frac{}{\text{len nil } Z} \text{len} - \text{nil}$$

Need to prove: if len nil n and reverse nil l, then len l n

- (1) reverse nil nil (By rev-nil)
- (2) len nil Z (by (1) and len-nil)

Case:
$$\frac{\text{len l n}}{\text{len cons}(n_1, l) (S n)} \text{len} - \text{cons}$$

Need to prove: if reverse cons(n_1 , l) l'', then len l'' (S n).

- (1) len l n and reverse l l' (By assumption)
- (2) len l' n (By (1) & I.H.)
- (3) reverse cons(n_1 , l) l'' (By assumption)
- (4) reverse l l', append l' n_1 l'' (By (3) and inversion of rev-cons)
- (5) len l'' (S n) (By (2), (4), Lemma 2)

QED.

$$\frac{}{\text{len nil } Z} \text{len} - \text{nil}$$

$$\frac{\text{len l n}}{\text{len cons}(n_1, l) (S n)} \text{len} - \text{cons}$$

$$\frac{\text{reverse } l_1 l_2 \quad \text{append } l_2 n l_2'}{\text{reverse cons}(n, l_1) l_2'} \text{rev} - \text{cons}$$

PROOF STRUCTURE

- Following is the structure you should use when proving something by rule induction (aka structure induction) **MUST HAVE!**

Theorem: If X then A.

Proof: By induction on the derivation of J.

(Hint: J is usually part of X. X is called assumption)

(Assuming definition of J has three rules: Foo-1, Foo-2, Bar)

$$\frac{(p1)premise1..(pn)premise_n}{conclusion} [Foo-1]$$

$$\frac{(p1)premise1..(pn)premise_n}{conclusion} [Foo-2]$$

$$\frac{(p1)premise1..(pn)premise_n}{conclusion} [Bar]$$

PROOF STRUCTURE (II)

Two column
format!

Case Foo-1:

- (1) ... [by (p1) and Lemma 1]
- (2) X [by assumption]
- (3) ... [by (1) and (2)]
-
- (n) A [by (n-3) and (n-1)]

One case
after another!

Case Foo-2:

Similar to case Foo-1.

PROOF STRUCTURE (III)

Case Bar:

- (1) ... [by (p1) and Lemma 1]
- (2) ... [by (p2) and I.H. on (p3)]
- (3) ... [by (1) and (2)]
-
- (n) A [by (n-3) and (n-1)]

RULES TO PROVE BY

- Clearly state the induction hypothesis. Convenient to say what you trying to prove (target property).
- Clearly state the proof methodology (what you are doing induction on).
- There should be one case for each rule in the inductive definition.
- Use a **two-column format**:
 - Left side: logical steps toward to target property.
 - Right side: reasoning for each step.
- In general, do not attempt to write your proof in English sentences. While some written explanations can be useful, normally they (attempt to) hide the fact that the proof is imprecise and has holes in it.
- Number your steps for easy reference.
- Always state where you use the induction hypothesis.

RULES TO PROVE BY (II)

- If two cases are very similar, you can prove the first and then say that the second follows similarly. Just be certain that the cases are really, truly similar. (For example, the case for projecting the first element of a pair and the case for projecting the second element of a pair are similar.)
- If for some reason you can't prove something in the middle of a proof (because you don't have time, you don't know how, etc.), please don't try to hide that fact. Use the fact you need and in the reasoning next to it, say something like: "I can't figure out how to conclude this, but it should be true".
- Always break down a proof into appropriate lemmas. The result of not introducing new lemmas where appropriate is usually that you try to proceed with your proof using the wrong induction hypothesis.
- If you need new judgement forms, make sure you clearly define it before you begin using it.

INDUCTION HYPOTHESIS STRUCTURE

- Depending on the structure of your induction hypothesis (i.e. the property to prove), you make different assumptions and therefore must prove different things:

Induction Hypothesis	Can Assume	Must Prove
If X and Y then A	X and Y	A
If X or Y then A	(1) X AND (2) Y	A A
If X then A and B	X	A and B
If X then A or B	X	A or B

- Notice in second case, you must prove two things, i.e., A must be true given just X, and given just Y.