Induction

Sections 5.1 and 5.2 of Rosen 7th Edition

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CSCE 235H Introduction to Discrete Structures (Honors)

Course web-page: cse.unl.edu/~cse235h

Questions: Piazza

Outline

- Motivation
- What is induction?
  - Viewed as: the Well-Ordering Principle, Universal Generalization
  - Formal Statement
  - 6 Examples
- Strong Induction
  - Definition
  - Examples: decomposition into product of primes, gcd

Motivation

- How can we prove the following proposition?

$$\forall x \in S\ P(x)$$

- For a finite set $S=\{s_1,s_2,\ldots,s_n\}$, we can prove that $P(x)$ holds for each element because of the equivalence

$$P(s_1) \wedge P(s_2) \wedge \ldots \wedge P(s_n)$$

- For an infinite set, we can try to use <u>universal generalization</u>
- Another, more sophisticated way is to use <u>*induction*</u>

What Is Induction?

- If a statement $P(n_0)$ is true for some nonnegative integer say $n_0=1$
- Suppose that we are able to prove that if P(k) is true for $k \geq n_0$, then P(k+1) is also true

$$P(k) \Rightarrow P(k+1)$$

- It follows from these two statement that P(n) is true for all $n \geq n_0$, that is

$$\forall n \geq n_0 \; P(n)$$

- The above is the basis of <u>induction</u>, a ‘widely’ used proof technique and a <u>very</u> powerful one

The Well-Ordering Principle

- Why induction is a legitimate proof technique?
- At its heart, induction is the Well Ordering Principle
- **Theorem:** Principle of Well Ordering. Every nonempty set of nonnegative integers has a least element
- Since, every such has a least element, we can form a basis case (using the least element as the basis case n_0)
- We can then proceed to establish that the set of integers $n \geq n_0$ such that P(n) is false is actually empty
- Thus, induction (both 'weak' and 'strong' forms) are logical equivalences of the well-ordering principle.

Another View

- To look at it in another way, assume that the statements

  (1) $P(n_o)$

  (2) $P(k) \Rightarrow P(k+1)$

  are true. We can now use a form of universal generalization as follows

- Say we choose an element c of the UoD. We wish to establish that P(c) is true. If $c=n_0$, then we are done

- Otherwise, we apply (2) above to get

  $$P(n_0) \Rightarrow P(n_0+1),\ P(n_0+1) \Rightarrow P(n_0+2),\ P(n_0+1) \Rightarrow P(n_0+3),\ \ldots,\ P(c-1) \Rightarrow P(c)$$

  Via a finite number of steps $(c-n_0)$ we get that P(c) is true.

- Because c is arbitrary, the universal generalization is established and

  $$\forall n \geq n_0\ P(n)$$

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Induction: Formal Definition (1)

- **Theorem**: Principle of Mathematical Induction

  Given a statement P concerning the integer n, suppose

  1. P is true for some particular integer n_0, $P(n_0)=1$
  2. If P is true for some particular integer $k \geq n_0$ then it is true for k+1: $P(k) \rightarrow P(k+1)$

  Then P is true for all integers $n \geq n_0$, that is

$$\forall n \geq n_0 \; P(n) \text{ is true}$$

Induction: Formal Definition (2)

- Showing that $P(n_0)$ holds for some initial integer n_0 is called the basis step
- The assumption $P(k)$ is called the inductive hypothesis
- Showing the implication $P(k) \rightarrow P(k+1)$ for every $k \geq n_0$ is called the inductive step
- Together, they are used to define mathematical induction
- Induction is expressed as an inference rule

$$[P(n_0) \land (\forall\, k \geq n_0\, P(k) \rightarrow P(k+1))] \rightarrow \forall n \geq n_0\, P(n)$$

Steps

1. Form the general statement
2. Form and verify the base case (basis step)
3. Form the inductive hypothesis
4. Prove the inductive step

Example A (1)

- Prove that $n^2 \leq 2^n$ for all $n \geq 5$ using induction
- We formalize the statement $P(n)=(n^2 \leq 2^n)$
- Our basis case is for n=5. We directly verify that

$$25 = 5^2 \leq 2^5 = 32$$

so P(5) is true and thus the basic step holds

- We need now to perform the inductive step

Example A (2)

- Assume P(k) holds (the inductive hypothesis). Thus, $k^2 \le 2^k$
- Now, we need to prove the inductive step. For all $k \ge 5$,

$(k+1)^2 = k^2+2k+1 < k^2 + 2k + k$ (because $k \ge 5 > 1$)

$< k^2 + 3k < k^2 + k \cdot k$ (because $k \ge 5 > 3$)

$< k^2 + k^2 = 2k^2$

- Using the inductive hypothesis ($k^2 \le 2^k$), we get

$$(k+1)^2 < 2k^2 \le 2 \cdot 2^k = 2^{k+1}$$

- Thus, P(k+1) holds

Example B (1)

- Prove that for any $n \geq 1$, $\Sigma_{i=1}^{n} (i^2) = n(n+1)(2n+1)/6$
- The basis case is easily verified $1^2=1= 1(1+1)(2+1)/6$
- We assume that P(k) holds for some $k \geq 1$, so

$$\Sigma_{i=1}^{k} (i^2) = k(k+1)(2k+1)/6$$

- We want to show that P(k+1) holds, that is

$$\Sigma_{i=1}^{k+1} (i^2) = (k+1)(k+2)(2k+3)/6$$

- We rewrite this sum as

$$\Sigma_{i=1}^{k+1} (i^2) = 1^2+2^2+..+k^2+(k+1)^2 = \Sigma_{i=1}^{k} (i^2) + (k+1)^2$$

Example B (2)

- We replace $\Sigma_{i=1}^{k} (i^2)$ by its value from the inductive hypothesis

$$\Sigma_{i=1}^{k+1} (i^2) = \Sigma_{i=1}^{k} (i^2) + (k+1)^2$$
$$= k(k+1)(2k+1)/6 + (k+1)^2$$
$$= k(k+1)(2k+1)/6 + 6(k+1)^2/6$$
$$= (k+1)[k(2k+1)+6(k+1)]/6$$
$$= (k+1)[2k^2+7k+6]/6$$
$$= (k+1)(k+2)(2k+3)/6$$

- Thus, we established that $P(k) \rightarrow P(k+1)$
- Thus, by the principle of mathematical induction we have

$$\forall n \geq 1, \Sigma_{i=1}^{n} (i^2) = n(n+1)(2n+1)/6$$

Example C (1)

- Prove that for any integer $n \geq 1$, $2^{2n}-1$ is divisible by 3
- Define P(n) to be the statement $3 \mid (2^{2n}-1)$
- We note that for the basis case n=1 we do have P(1)

$$2^{2 \cdot 1}-1 = 3 \text{ is divisible by } 3$$

- Next we assume that P(k) holds. That is, there exists some integer u such that

$$2^{2k}-1 = 3u$$

- We must prove that P(k+1) holds. That is, $2^{2(k+1)}-1$ is divisible by 3

Example C (2)

- Note that: $2^{2(k+1)} - 1 = 2^2 2^{2k} - 1 = 4.2^{2k} - 1$
- The inductive hypothesis: $2^{2k} - 1 = 3u \Rightarrow 2^{2k} = 3u+1$
- Thus: $2^{2(k+1)} - 1 = 4 \cdot 2^{2k} - 1 = 4(3u+1) - 1$

  $= 12u+4-1$

  $= 12u+3$

  $= 3(4u+1)$, a multiple of 3

- We conclude, by the principle of mathematical induction, for any integer $n \geq 1$, $2^{2n}-1$ is divisible by 3

Example D

- Prove that $n! > 2^n$ for all $n \geq 4$
- The basis case holds for $n=4$ because $4!=24>2^4=16$
- We assume that $k! > 2^k$ for some integer $k \geq 4$ (which is our inductive hypothesis)
- We must prove the $P(k+1)$ holds

$$(k+1)! = k!\,(k+1) > 2^k\,(k+1)$$

- Because $k \geq 4$, $k+1 \geq 5 > 2$, thus

$$(k+1)! > 2^k\,(k+1) > 2^k \cdot 2 = 2^{k+1}$$

- Thus by the principal of mathematical induction, we have $n! > 2^n$ for all $n \geq 4$

Example E: Summation

- Show that $\Sigma_{i=1}{}^{n}\,(i^3) = (\Sigma_{i=1}{}^{n}\, i)^2$ for all $n \geq 1$
- The basis case is trivial: for $n = 1$, $1^3 = 1^2$
- The inductive hypothesis assumes that for some $n \geq 1$ we have $\Sigma_{i=1}{}^{k}\,(i^3) = (\Sigma_{i=1}{}^{k}\, i)^2$
- We now consider the summation for (k+1): $\Sigma_{i=1}{}^{k+1}\,(i^3)$

$= (\Sigma_{i=1}{}^{k}\, i)^2 + (k+1)^3 \;= (\, k(k+1)/2\,)^2 + (k+1)^3$

$= (\, k^2(k+1)^2 + 4(k+1)^3\,) / 2^2 \;= (k+1)^2\,(k^2 + 4(k+1)\,) / 2^2$

$= (k+1)^2\,(\, k^2 + 4k + 4\,) / 2^2 \;= (k+1)^2\,(\, k+2)^2 / 2^2$

$= ((k+1)(k+2) / 2)^{2}$

- Thus, by the PMI, the equality holds

Example F: Derivatives

- Show that for all $n \geq 1$ and $f(x)= x^n$, we have $f'(x)= nx^{n-1}$
- Verifying the basis case for n=1:

  $f'(x) = \lim_{h \to 0} (f(x_0+h)-f(x_0)) / h$

  $= \lim_{h \to 0} ((x_0+h)^1-(x_0^1)) / h = 1 = 1 \cdot x^0$
- Now, assume that the inductive hypothesis holds for some k, $f(x) = x^k$, we have $f'(x) = kx^{k-1}$
- Now, consider $f_2(x) = x^{k+1} = x^k \cdot x$
- Using the product rule: $f'_2(x) = (x^k)' \cdot x + (x^k) \cdot x'$
- Thus, $f'_2(x) = kx^{k-1} \cdot x + x^k \cdot 1 = kx^k + x^k = (k+1)x^k$

The Bad Example: Example G

- Consider the proof for: All of you will receive the same grade
- Let P(n) be the statement: "Every set of n students will receive the same grade"
- Clearly, P(1) is true. So the basis case holds
- Now assume P(k) holds, the inductive hypothesis
- Given a group of k students, apply P(k) to $\{s_1, s_2, \ldots, s_k\}$
- Now, separately apply the inductive hypothesis to the subset $\{s_2, s_3, \ldots, s_{k+1}\}$
- Combining these two facts, we get $\{s_1, s_2, \ldots, s_{k+1}\}$. Thus, P(k+1) holds.
- Hence, P(n) is true for all students

Example G: Where is the Error?

- The mistake is not the basis case: P(1) is true
- Also, it is the case that, say, P(73) $\Rightarrow$ P(74)
- So, this is cannot be the mistake
- The error is in P(1) $\Rightarrow$ P(2), which cannot hold
- We cannot combine the two inductive hypotheses to get P(2)

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- **Strong Induction**
  - **Definition**
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Strong Induction

- **Theorem**: Principle of Mathematical Induction (Strong Form)

  Given a statement P concerning an integer n, suppose

  1. P is true for some particular integer n_0, $P(n_0)=1$
  2. If $k \geq n_0$ is any integer and P is true for all integers m in the range $n_0 \leq m < k$, then it is true also for k

  Then, P is true for all integers $n \geq n_0$, i.e.

$$\forall\, n \geq n_0\ P(n) \text{ holds}$$

MPI and its Strong Form

- Despite the name, the strong form of PMI is not a stronger proof technique than PMI
- In fact, we have the following Lemma
- **Lemma**: The following are equivalent
  - The Well Ordering Principle
  - The Principle of Mathematical Induction
  - The Principle of Mathematical Induction, Strong Form

Strong Form: Example A (1)

- **Fundamental Theorem of Arithmetic** (page 211): For any integer n≥2 can be written uniquely as
  - A prime or
  - As the product of primes
- Prove using the strong form of induction to
- **Definition** (page 210)
  - **Prime**: A positive integer p greater than 1 is called prime iff the only positive factors of p are 1 and p.
  - **Composite**: A positive integer that is greater than 1 and is not prime is called composite
- According to the definition, 1 is not a prime

Strong Form: Example A (2)

1. Let P(n) be the statement: “n is a prime or can be written uniquely as a product of primes.”
2. The basis case holds: P(2)=2 and 2 is a prime.

Strong Form: Example A (3)

3. We make our inductive hypothesis. Here we assume that the predicate P holds for all integers less than some integer $k \geq 2$, i.e., we assume that:

$$P(2) \wedge P(3) \wedge P(4) \wedge \ldots \wedge P(k) \text{ is true}$$

4. We want to show that this implies that $P(k+1)$ holds. We consider two cases:
   - $k+1$ is prime, then $P(k+1)$ holds. We are done.
   - $k+1$ is a composite.

     $k+1$ has two factors u,v, $2 \leq u,v < k+1$ such that $k+1=u \cdot v$

     By the inductive hypothesis $u=\Pi_i\, p_i$ $v= \Pi_j\, p_j$, and p_i,p_j prime

     Thus, $k+1=\Pi_i\, p_i\, \Pi_j\, p_j$

So, by the strong form of PMI, $P(k+1)$ holds **QED**

Strong Form: Example B (1)

- **Notation:**
  - gcd(a,b): the greatest common divisor of a and b
    - Example: gcd(27, 15)=3, gcd(35,28)=7
  - gcd(a,b)=1 ⇔ a, b are mutually prime
    - Example: gcd(15,14)=1, gcd(35,18)=1
- **Lemma**: If a,b $\in N$ are such that gcd(a,b)=1 then there are integers s,t such that

$$\gcd(a,b)=1=sa+tb$$

- **Question:** Prove the above lemma using the strong form of induction

Background Knowledge

- Prove that: gcd(a,b)= gcd(a,b-a)
- Proof: Assume gcd(a,b)=k and gcd(a,b-a)=k'
  - gcd(a,b)=k $\Rightarrow$ k divides a and b

    $\Rightarrow$ k divides a and (b-a) $\Rightarrow$ k divides k'
  - gcd(a,b-a)=k' $\Rightarrow$ k' divides a and b-a

    $\Rightarrow$ k' divides a and a+(b-a)=b $\Rightarrow$ k' divides k
  - (k divides k') and (k' divides k) $\Rightarrow$ k = k'

    $\Rightarrow$ gcd(a,b)= gcd(a,b-a)

(Lame) Alternative Proof

- Prove that gcd(a,b)=1 $\Rightarrow$ gcd(a,b-a)=1
- We prove the contrapositive
  - Assume gcd(a,b-a)$\neq$ 1 $\Rightarrow$ $\exists$ k$\in$Z, k$\neq$1 k divides a and b-a $\Rightarrow$ $\exists$ m,n$\in$Z a=km and b-a=kn

    $\Rightarrow$ a+(b-a)=k(m+n) $\Rightarrow$ b=k(m+n) $\Rightarrow$ k divides b
  - k$\neq$1 divides a and divides b $\Rightarrow$ gcd(a,b) $\neq$ 1
- But, don't prove a special case when you have the more general one (see previous slide..)

Strong Form: Example B (2)

1. Let P(n) be the statement

   $(a,b \in N) \wedge (\gcd(a,b)=1) \wedge (a+b=n) \Rightarrow \exists s,t \in Z, sa+tb=1$

2. Our basis case is when n=2 because a=b=1.

   For s=1, t=0, the statement P(2) is satisfied (sa+tb=1.1+1.0=1)

3. We form the inductive hypothesis P(k):
   - For $k \in N$, $k \geq 2$
   - For all i, $2 \leq i \leq k$ P(a+b=k) holds
   - For $a,b \in N$, $(\gcd(a,b)=1) \wedge (a+b=k)$ $\exists s,t \in Z$, $sa+tb=1$

4. Given the inductive hypothesis, we prove P(a+b = k+1)

   We consider three cases: a=b, a<b, a>b

Strong Form: Example B (3)

Case 1: a=b

- In this case: gcd(a,b) = gcd(a,a) *Because a=b*

  = a *By definition*

  = 1 *See assumption*

- gcd(a,b)=1 $\Rightarrow$ a=b=1

  $\Rightarrow$ We have the basis case,

  P(a+b)=P(2), which holds

Strong Form: Example B (4)

Case 2: a<b

- $b > a \Rightarrow b - a > 0$. So $\gcd(a,b)=\gcd(a,b-a)=1$
- Further: $2 \leq a+(b-a)=(a+b)-a =(k+1)-a \leq k \Rightarrow a+(b-a) \leq k$
- Applying the inductive hypothesis $P(a+(b-a))$
  $(a,(b-a) \in N) \wedge (\gcd(a,b-a)=1) \wedge (a+(b-a)=b) \Rightarrow \exists s_0,t_0 \in Z,\ s_0a+t_0(b-a)=1$
- Thus, $\exists s_0,t_0 \in Z$ such that $(s_0-t_0)a + t_0b=1$
- So, for $s,t \in Z$ where $s=s_0-t_0$, $t=t_0$ we have $sa + tb=1$
- Thus, $P(k+1)$ is established for this case

Strong Form: Example B (5)

Case 2: a>b

- This case is completely symmetric to case 2
- We use a-b instead of a-b

- Because the three cases handle every possibility, we have established that P(k+1) holds
- Thus, by the PMI strong form, the Lemma holds. **QED**

Template

- In order to prove by induction
  - Some mathematical theorem, or
  - $\forall\ n \geq n_0\ P(n)$
- Follow the template
  1. State a propositional predicate

     P(n): some statement involving n
  2. Form and verify the basis case (basis step)
  3. Form the inductive hypothesis (assume P(k))
  4. Prove the inductive step (prove P(k+1))

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