



Induction

Lecture 5
CS2110 – Summer 2008

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Overview

- Recursion
 - A programming strategy that solves a problem by reducing it to simpler or smaller instance(s) of the same problem
- Induction
 - A mathematical strategy for proving statements about natural numbers 0, 1, 2, ... (or more generally, about inductively defined objects)
- Induction and recursion are very closely related

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Defining Functions

- It is often useful to describe a function in different ways
 - Let $S : \text{int} \rightarrow \text{int}$ be the function where $S(n)$ is the sum of the integers from 0 to n . For example,
 $S(0) = 0$ $S(3) = 0+1+2+3 = 6$
 - Definition: iterative form
 - $S(n) = 0+1+ \dots + n = \sum_{i=0}^n i$
 - Recursive definition
 - $S(0) = 0$
 - $S(n) = n + S(n-1)$ for $n > 0$
 - Another characterization: closed form
 - $S(n) = n(n+1)/2$


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Sum of Squares

- A more complex example
 - Let $SQ : \text{int} \rightarrow \text{int}$ be the function that gives the sum of the squares of integers from 0 to n :
 $SQ(0) = 0$ $SQ(3) = 0^2 + 1^2 + 2^2 + 3^2 = 14$
- Definition (iterative form): $SQ(n) = 0^2 + 1^2 + \dots + n^2$
- Is there an equivalent closed-form expression?

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Closed-Form Expression for $SQ(n)$

- Sum of integers between 0 through n was $n(n+1)/2$ which is a quadratic in n
- Inspired guess: perhaps sum of squares of integers between 0 through n is a cubic in n 
- Conjecture: $SQ(n) = an^3 + bn^2 + cn + d$ where a, b, c, d are unknown coefficients
- How can we find the values of the four unknowns?
 - Idea: Use any 4 values of n to generate 4 linear equations, and then solve

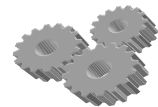
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Finding Coefficients

$$SQ(n) = 0^2 + 1^2 + \dots + n^2 = an^3 + bn^2 + cn + d$$

- Use $n = 0, 1, 2, 3$

| | | |
|-----------|----|--|
| $SQ(0) =$ | 0 | $= a \cdot 0 + b \cdot 0 + c \cdot 0 + d$ |
| $SQ(1) =$ | 1 | $= a \cdot 1 + b \cdot 1 + c \cdot 1 + d$ |
| $SQ(2) =$ | 5 | $= a \cdot 8 + b \cdot 4 + c \cdot 2 + d$ |
| $SQ(3) =$ | 14 | $= a \cdot 27 + b \cdot 9 + c \cdot 3 + d$ |



Solve these 4 equations to get

$$a = 1/3 \quad b = 1/2 \quad c = 1/6 \quad d = 0$$

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Is the Formula Correct?

- This suggests

$$\begin{aligned} \text{SQ}(n) &= 0^2 + 1^2 + \dots + n^2 \\ &= n^3/3 + n^2/2 + n/6 \\ &= n(n+1)(2n+1)/6 \end{aligned}$$

- Question: Is this closed-form solution true for all n ?
 - Remember, we only used $n = 0, 1, 2, 3$ to determine these coefficients
 - We do not know that the closed-form expression is valid for other values of n

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One Approach

- Try a few other values of n to see if they work.
 - Try $n = 5$: $\text{SQ}(n) = 0+1+4+9+16+25 = 55$
 - Closed-form expression: $5 \cdot 6 \cdot 11 / 6 = 55$
 - Works!
- Try some more values...
- We can never prove validity of the closed-form solution for all values of n this way, since there are an infinite number of values of n

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A Recursive Definition

- To solve this problem, let's express $\text{SQ}(n)$ in a different way:

$$\text{SQ}(n) = \boxed{0^2 + 1^2 + \dots + (n-1)^2} + n^2$$

- The part in the box is just $\text{SQ}(n-1)$

- This leads to the following recursive definition

$$\begin{aligned} \text{SQ}(0) &= 0 && \text{Base Case} \\ \text{SQ}(n) &= \text{SQ}(n-1) + n^2, \quad n > 0 && \text{Recursive Case} \end{aligned}$$

- Thus,

$$\begin{aligned} \text{SQ}(4) &= \text{SQ}(3) + 4^2 \\ &= \text{SQ}(2) + 3^2 + 4^2 \\ &= \text{SQ}(1) + 2^2 + 3^2 + 4^2 \\ &= \text{SQ}(0) + 1^2 + 2^2 + 3^2 + 4^2 \\ &= 0 + 1^2 + 2^2 + 3^2 + 4^2 \end{aligned}$$

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Are These Two Functions Equal?

- SQ_r ($r = \text{recursive}$)

$$\begin{aligned} \text{SQ}_r(0) &= 0 \\ \text{SQ}_r(n) &= \text{SQ}_r(n-1) + n^2, \quad n > 0 \end{aligned}$$

- SQ_c ($c = \text{closed-form}$)

$$\text{SQ}_c(n) = n(n+1)(2n+1)/6$$

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Induction over Integers

- To prove that some property $P(n)$ holds for all integers $n \geq 0$,
 - Basis: Show that $P(0)$ is true
 - Induction Step: Assuming that $P(k)$ is true for an unspecified integer k , show that $P(k+1)$ is true
- Conclusion: Because we could have picked any k , we conclude that $P(n)$ holds for all integers $n \geq 0$

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- Assume equally spaced dominos, and assume that spacing between dominos is less than domino length
- How would you argue that all dominos would fall?
- Dumb argument:
 - Domino 0 falls because we push it over
 - Domino 0 hits domino 1, therefore domino 1 falls
 - Domino 1 hits domino 2, therefore domino 2 falls
 - Domino 2 hits domino 3, therefore domino 3 falls
 - ...
- Is there a more compact argument we can make?

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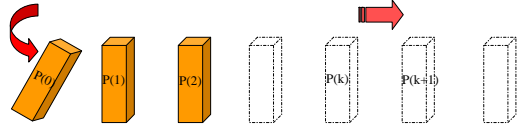
Better Argument

- Argument:
 - Domino 0 falls because we push it over (Base Case or Basis)
 - Assume that domino k falls over (Induction Hypothesis)
 - Because domino k's length is larger than inter-domino spacing, it will knock over domino k+1 (Inductive Step)
 - Because we could have picked any domino to be the kth one, we conclude that all dominoes will fall over (Conclusion)
- This is an inductive argument
- This version is called *weak induction*
 - There is also *strong induction* (later)
- Not only is this argument more compact, it works for an arbitrary number of dominoes!

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$SQ_r(n) = SQ_c(n)$ for all n ?

- Define $P(n)$ as $SQ_r(n) = SQ_c(n)$



- Prove $P(0)$
- Assume $P(k)$ for unspecified k , and then prove $P(k+1)$ under this assumption

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Proof (by Induction)

$$SQ_r(0) = 0$$

$$SQ_c(n) = SQ_c(n-1) + n^2, \quad n > 0$$

$$SQ_c(n) = n(n+1)(2n+1)/6$$

Let $P(n)$ be the proposition $SQ_r(n) = SQ_c(n)$. Prove $P(n) \forall n \geq 0$.

- Basis: $P(0)$ holds because $SQ_r(0) = 0$ and $SQ_c(0) = 0$ by definition
- Induction Hypothesis: Assume $SQ_r(k) = SQ_c(k)$
- Inductive Step:

| | | |
|-------------|------------------------------|------------------------------|
| $SQ_r(k+1)$ | $= SQ_r(k) + (k+1)^2$ | by definition of $SQ_r(k+1)$ |
| | $= SQ_c(k) + (k+1)^2$ | by Induction Hypothesis |
| | $= k(k+1)(2k+1)/6 + (k+1)^2$ | by definition of $SQ_c(k)$ |
| | $= (k+1)(k+2)(2k+3)/6$ | algebra |
| | $= SQ_c(k+1)$ | by definition of $SQ_c(k+1)$ |
- Conclusion: $SQ_r(n) = SQ_c(n)$ for all $n \geq 0$

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Another Example

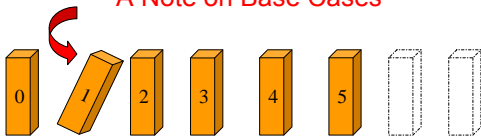
Prove that $0+1+\dots+n = n(n+1)/2 \quad \forall n \geq 0$.

- Basis: Obviously holds for $n = 0$
- Induction Hypothesis: Assume $0+1+\dots+k = k(k+1)/2$
- Inductive Step:

| | | |
|-------------------|---------------------------|---------|
| $0+1+\dots+(k+1)$ | $= [0+1+\dots+k] + (k+1)$ | by def |
| | $= k(k+1)/2 + (k+1)$ | by I.H. |
| | $= (k+1)(k+2)/2$ | algebra |
- Conclusion: $0+1+\dots+n = n(n+1)/2$ for all $n \geq 0$

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A Note on Base Cases



- Sometimes we are interested in showing some proposition is true for integers $\geq b$
- Intuition: we knock over domino b , and dominoes in front get knocked over; not interested in $0, 1, \dots, (b-1)$
- In general, the base case in induction does not have to be 0
- If base case is some integer b
 - Induction proves the proposition for $n = b, b+1, b+2, \dots$
 - Does not say anything about $n = 0, 1, \dots, b-1$

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Weak Induction: Nonzero Base Case

Claim: You can make any amount of postage above 8¢ with some combination of 3¢ and 5¢ stamps

- Basis: True for 8¢: $8 = 3 + 5$
- Induction Hypothesis: Suppose true for some $k \geq 8$
- Inductive Step:
 - If used a 5¢ stamp to make k , replace it by two 3¢ stamps. Get $k+1$.
 - If did not use a 5¢ stamp to make k , must have used at least three 3¢ stamps. Replace three 3¢ stamps by two 5¢ stamps. Get $k+1$.
- Conclusion: Any amount of postage above 8¢ can be made with some combination of 3¢ and 5¢ stamps

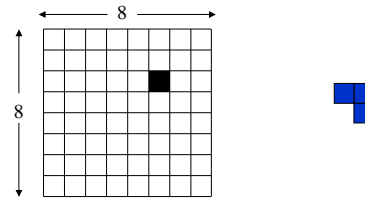
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What are the “Dominos”?

- In some problems, it can be tricky to determine how to set up the induction
- This is particularly true for geometric problems that can be attacked using induction

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A Tiling Problem



- A chessboard has one square cut out of it
- Can the remaining board be tiled using tiles of the shape shown in the picture (rotation allowed)?
- Not obvious that we can use induction!

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Proof Outline

Consider boards of size $2^n \times 2^n$ for $n = 1, 2, \dots$

- **Basis:** Show that tiling is possible for 2×2 board
- **Induction Hypothesis:** Assume the $2^k \times 2^k$ board can be tiled
- **Inductive Step:** Using I.H. show that the $2^{k+1} \times 2^{k+1}$ board can be tiled
- **Conclusion:** Any $2^n \times 2^n$ board can be tiled, $n = 1, 2, \dots$
 - Our chessboard (8×8) is a special case of this argument
 - We will have proven the 8×8 special case by solving a more general problem!

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Basis



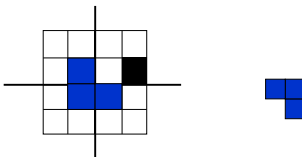
2 x 2 board



- The 2×2 board can be tiled regardless of which one of the four pieces has been omitted

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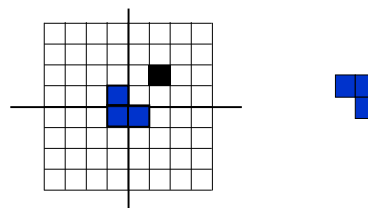
4 x 4 Case



- Divide the 4×4 board into four 2×2 sub-boards
- One of the four sub-boards has the missing piece
 - By the I.H., that sub-board can be tiled since it is a 2×2 board with a missing piece
- Tile the center squares of the three remaining sub-boards as shown
 - This leaves three 2×2 boards, each with a missing piece
 - We know these can be tiled by the Induction Hypothesis

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$2^{k+1} \times 2^{k+1}$ case



- Divide board into four sub-boards and tile the center squares of the three complete sub-boards
- The remaining portions of the sub-boards can be tiled by the I.H. (which assumes we can tile $2^k \times 2^k$ boards)

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When Induction Fails

- Sometimes an inductive proof strategy for some proposition may fail
- This does not necessarily mean that the proposition is wrong
 - It may just mean that the particular inductive strategy you are using is the wrong choice
- A different induction hypothesis (or a different proof strategy altogether) may succeed

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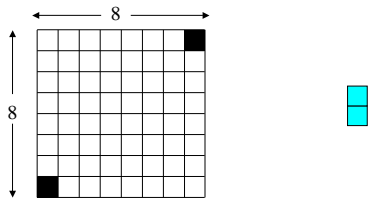
Tiling Example (Poor Strategy)

Let's try a different induction strategy

- Proposition
 - Any $n \times n$ board with one missing square can be tiled
- Problem
 - A 3×3 board with one missing square has 8 remaining squares, but our tile has 3 squares; tiling is impossible
- Thus, any attempt to give an inductive proof of this proposition *must fail*
- Note that this failed proof does not tell us anything about the 8×8 case

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A Seemingly Similar Tiling Problem



- A chessboard has opposite corners cut out of it. Can the remaining board be tiled using tiles of the shape shown in the picture (rotation allowed)?
- Induction fails here. Why? (Well...for one thing, this board can't be tiled with dominos.)

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Strong Induction

- We want to prove that some property P holds for all n
- Weak induction
 - $P(0)$: Show that property P is true for 0
 - $P(k) \Rightarrow P(k+1)$: Show that if property P is true for k , it is true for $k+1$
 - Conclude that $P(n)$ holds for all n
- Strong induction
 - $P(0)$: Show that property P is true for 0
 - $P(0)$ and $P(1)$ and ... and $P(k) \Rightarrow P(k+1)$: show that if P is true for numbers less than or equal to k , it is true for $k+1$
 - Conclude that $P(n)$ holds for all n
- Both proof techniques are equally powerful

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Conclusion

- Induction is a powerful proof technique
- Recursion is a powerful programming technique
- Induction and recursion are closely related
 - We can use induction to prove correctness and complexity results about recursive programs

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