Mathematical Induction
(Based on [Manber 1989])

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The Standard Induction Principle

- Let T be a theorem that includes a parameter n whose value can be any natural number.
- Here, natural numbers are positive integers, i.e., 1, 2, 3, ..., excluding 0 (sometimes we may include 0).
- To prove T, it suffices to prove the following two conditions:
  - ☀ T holds for $n = 1$. (Base case)
  - ☀ For every $n > 1$, if T holds for $n - 1$, then T holds for n. (Inductive step)
- The assumption in the inductive step that T holds for $n - 1$ is called the *induction hypothesis*.

A Starter

Theorem (2.1)

For all natural numbers x and n, $x^n - 1$ is divisible by $x - 1$.

Proof.

(Suggestion: try to follow the structure of this proof when you present a proof by induction.)

The proof is by induction on n.

Base case: $x - 1$ is trivially divisible by $x - 1$.

Inductive step: $x^n - 1 = x(x^{n-1} - 1) + (x - 1)$. $x^{n-1} - 1$ is divisible by $x - 1$ *from the induction hypothesis* and $x - 1$ is divisible by $x - 1$. Hence, $x^n - 1$ is divisible by $x - 1$. $\qquad\square$

Note: a is divisible by b if there exists an integer c such that $a = b \times c$.

Variants of Induction Principle

Theorem

If a statement P, with a parameter n, is true for n = 1, and if, for every n ≥ 1, the truth of P for n implies its truth for n + 1, then P is true for all natural numbers.

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If a statement P, with a parameter n, is true for n = 1, and if, for every n > 1, the truth of P for all natural numbers < n implies its truth for n, then P is true for all natural numbers.

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Theorem

If a statement P, with a parameter n, is true for n = 1 and for n = 2, and if, for every n > 2, the truth of P for n − 2 implies its truth for n, then P is true for all natural numbers.

Design by Induction: First Glimpse

Problem

Given two sorted arrays $A[1..m]$ and $B[1..n]$ of positive integers, find their smallest common element; returns 0 if no common element is found.

- Assume the elements of each array are in ascending order.
- **Obvious solution**: take one element at a time from A and find out if it is also in B (or the other way around).

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- 🌐 Assume the elements of each array are in ascending order.
- 🌐 **Obvious solution**: take one element at a time from A and find out if it is also in B (or the other way around).
- 🌐 How efficient is this solution?
- 🌐 Can we do better?

Design by Induction: First Glimpse (cont.)

🔵 There are $m + n$ elements to begin with.

🔵 Can we pick out one element such that either (1) it is the element we look for or (2) it can be ruled out from subsequent searches?

🔵 In the second case, we are left with the same problem but with $m + n - 1$ elements?

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- In the second case, we are left with the same problem but with $m + n - 1$ elements?

- **Idea**: compare the current first elements of A and B.
    1. If they are equal, then we are done.
    2. If not, the smaller one cannot be the smallest common element.

Design by Induction: First Glimpse (cont.)

Below is the complete solution:

Algorithm

Algorithm SCE(A, m, B, n) : *integer*;
begin
    if $m = 0$ *or* $n = 0$ **then** $SCE := 0$;
    if $A[1] = B[1]$ **then**
      $SCE := A[1]$;
    else if $A[1] < B[1]$ **then**
         $SCE := SCE(A[2..m], m - 1, B, n)$;
    else $SCE := SCE(A, m, B[2..n], n - 1)$;
end

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🌐 Computations carried out by a computer/machine can, in essence, be understood as mathematical functions.

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    - various manipulations of the objects become functions on the corresponding mathematical structures.

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☀ objects/things in a practical domain must be modeled as (mostly discrete) mathematical structures/sets, and

☀ various manipulations of the objects become functions on the corresponding mathematical structures.

● Many mathematical structures are naturally defined by induction.

● Functions on inductive structures are also naturally defined by induction (recursion).

Another Simple Example

Theorem (2.4)

If n is a natural number and $1 + x > 0$, then $(1 + x)^n \geq 1 + nx$.

- Below are the key steps:

$$
\begin{aligned}
(1 + x)^{n+1} &= (1 + x)(1 + x)^n \\
&\quad \{\text{induction hypothesis and } 1 + x > 0\} \\
&\geq (1 + x)(1 + nx) \\
&= 1 + (n + 1)x + nx^2 \\
&\geq 1 + (n + 1)x
\end{aligned}
$$

- The main point here is that we should be clear about how conditions listed in the theorem are used.

Proving vs. Computing

Theorem (2.2)

$1 + 2 + \cdots + n = \frac{n(n+1)}{2}$.

- This can be easily proven by induction.
- Key steps: $1 + 2 + \cdots + n + (n+1) = \frac{n(n+1)}{2} + (n+1) = \frac{n^2+n+2n+2}{2} = \frac{n^2+3n+2}{2} = \frac{(n+1)(n+2)}{2} = \frac{(n+1)((n+1)+1)}{2}$.

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⦿ What if we are asked to compute the sum of a series?

Proving vs. Computing

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🔵 Induction seems to be useful only if we already know the sum.

🔵 What if we are asked to compute the sum of a series?

🔵 Let's try $8 + 13 + 18 + 23 + \cdots + (3 + 5n)$.

Proving vs. Computing (cont.)

- **Idea**: guess and then verify by an inductive proof!
- The sum should be of the form $an^2 + bn + c$.
- By checking $n = 1$, 2, and 3, we get $\frac{5}{2}n^2 + \frac{11}{2}n$.
- Verify this for all n, i.e., the following theorem, by induction.

Theorem (2.3)

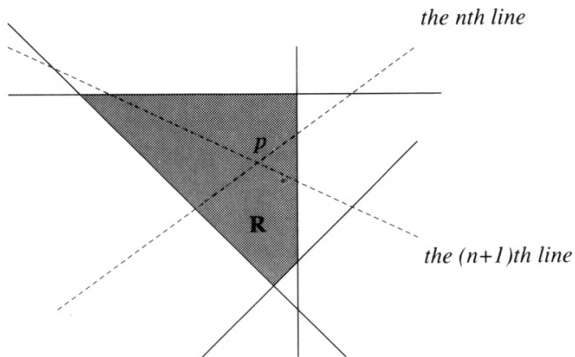$8 + 13 + 18 + 23 + \cdots + (3 + 5n) = \frac{5}{2}n^2 + \frac{11}{2}n$.

Counting Regions

Figure 2.1 $n + 1$ lines in general position.

Source: [Manber 1989].

Counting Regions (cont.)

Theorem (2.5)

The number of regions in the plane formed by n lines in general position is $\frac{n(n+1)}{2} + 1$.

A set of lines are in **general position** if (1) no two lines are parallel and (2) no three lines intersect at a common point.

Counting Regions (cont.)

Theorem (2.5)

The number of regions in the plane formed by n lines in general position is $\frac{n(n+1)}{2} + 1$.

A set of lines are in **general position** if (1) no two lines are parallel and (2) no three lines intersect at a common point.

🌐 We observe that $\frac{n(n+1)}{2} = 1 + 2 + \cdots + n$.

🌐 So, it suffices to prove the following:

Lemma

Adding one more line (the n-th line) to $n - 1$ lines in general position in the plane increases the number of regions by n.

A Summation Problem

$$
\begin{array}{rcl}
1 & = & 1 \\
3 + 5 & = & 8 \\
7 + 9 + 11 & = & 27 \\
13 + 15 + 17 + 19 & = & 64 \\
21 + 23 + 25 + 27 + 29 & = & 125
\end{array}
$$

Theorem

The sum of row n in the triangle is n^3.

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1 &= 1 \\
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\end{aligned}
$$

Theorem

The sum of row n in the triangle is n^3.

Examine the difference between rows $i + 1$ and i ...

Lemma

The last number in row $n + 1$ is $n^2 + 3n + 1$.

A Simple Inequality

Theorem (2.7)

$\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \cdots + \frac{1}{2^n} < 1$, for all $n \geq 1$.

🔵 There are at least two ways to select n terms from $n + 1$ terms.

1. $(\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \cdots + \frac{1}{2^n}) + \frac{1}{2^{n+1}}$.

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● There are at least two ways to select n terms from $n+1$ terms.
   1. $(\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \cdots + \frac{1}{2^n}) + \frac{1}{2^{n+1}}$.
   2. $\frac{1}{2} + (\frac{1}{4} + \frac{1}{8} + \cdots + \frac{1}{2^n} + \frac{1}{2^{n+1}})$.

● The second one leads to a successful inductive proof:

$$\frac{1}{2} + (\frac{1}{4} + \frac{1}{8} + \cdots + \frac{1}{2^n} + \frac{1}{2^{n+1}})$$
$$= \frac{1}{2} + \frac{1}{2}(\frac{1}{2} + \frac{1}{4} + \cdots + \frac{1}{2^{n-1}} + \frac{1}{2^n})$$
$$< \frac{1}{2} + \frac{1}{2}$$
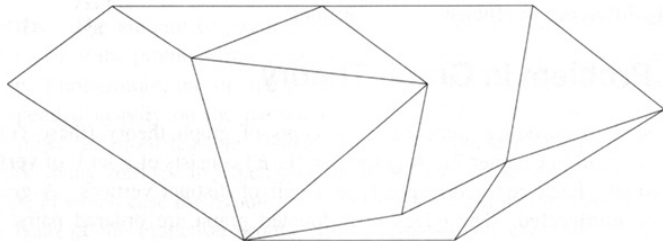$$= 1$$

Euler's Formula

Figure 2.2 A planar map with 11 vertices, 19 edges, and 10 faces.

Source: [Manber 1989].

Euler's Formula (cont.)

Theorem (2.8)

The number of vertices (V), edges (E), and faces (F) in an arbitrary connected planar graph are related by the formula $V + F = E + 2$.

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The number of vertices (V), edges (E), and faces (F) in an arbitrary connected planar graph are related by the formula $V + F = E + 2$.

The proof is by induction on the number of faces.
Base case: graphs with only one face are trees ...

Lemma

A tree with n vertices has $n - 1$ edges.

Inductive step: for a graph with more than one faces, there must be a cycle in the graph. Remove one edge from the cyle ...

Gray Codes

- A **Gray code** (after Frank Gray) for *n* objects is a binary-encoding scheme for naming the *n* objects such that the *n* names can be arranged in a *circular* list where *any two adjacent names differ by only one bit*.

- Examples:
    - 00, 01, 11, 10
    - 000, 001, 011, 010, 110, 111, 101, 100
    - 000, 001, 011, 111, 101, 100

Gray Codes (cont.)

Theorem (2.10)

There exist Gray codes of length $\frac{k}{2}$ for any positive even integer k.

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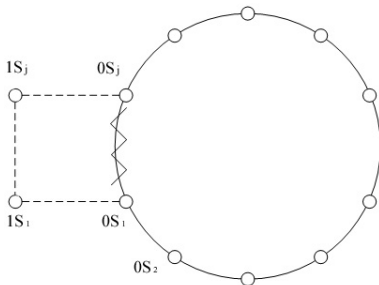

Figure 2.3 Constructing a Gray code of size $2k$

Source: [Manber 1989] (adapted).

Note: j in the figure equals $2(k-1)$ and hence $j+2$ equals $2k$.

Gray Codes (cont.)

Theorem (2.10+)

There exist Gray codes of length $\log_2 k$ for any positive integer k that is a power of 2.

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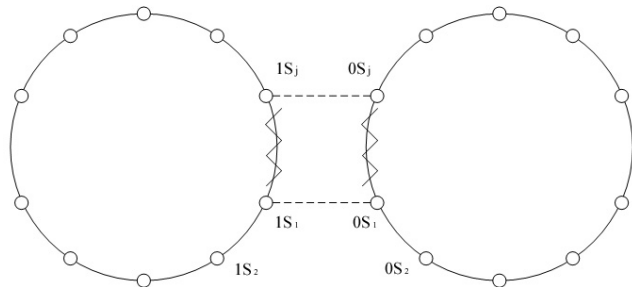

Figure 2.4 Constructing a Gray code from two smaller ones

Source: [Manber 1989] (adapted).

Gray Codes (cont.)

- 00, 01, 11, 10 (for 2^2 objects)
- 000, 001, 011, 010 (add a 0)
- 100, 101, 111, 110 (add a 1)
- Combine the preceding two codes (read the second in reversed order):
  000, 001, 011, 010, 110, 111, 101, 100 (for 2^3 objects)

Theorem (2.11−)

There exist Gray codes of length $\lceil \log_2 k \rceil$ for any positive even integer k.

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To generalize the result and ease the proof, we allow a Gray code to be *open* where the last name and the first name may differ by more than one bit.

Theorem (2.11)

There exist Gray codes of length $\lceil \log_2 k \rceil$ for any positive integer $k \geq 2$. The Gray codes for the even values of k are closed, and the Gray codes for odd values of k are open.

Gray Codes (cont.)

- 00, 01, 11 (open Gray code for 3 objects)
- 000, 001, 011 (add a 0)
- 100, 101, 111 (add a 1)
- Combine the preceding two codes (read the second in reversed order):
  000, 001, 011, 111, 101, 100 (closed Gray code for 6 objects)
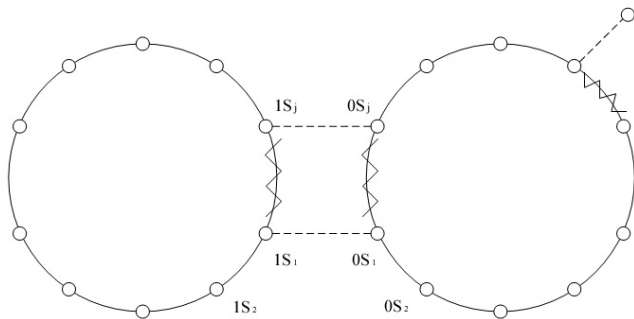
Gray Codes (cont.)

Figure 2.5 Constructing an open Gray code

Source: [Manber 1989] (adapted).

Arithmetic vs. Geometric Mean

Theorem (2.13)

If $x_1, x_2, \ldots, x_n$ are all positive numbers, then
$(x_1 x_2 \cdots x_n)^{\frac{1}{n}} \leq \dfrac{x_1 + x_2 + \cdots + x_n}{n}$.

Arithmetic vs. Geometric Mean

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$(x_1 x_2 \cdots x_n)^{\frac{1}{n}} \leq \dfrac{x_1 + x_2 + \cdots + x_n}{n}$.

First use the standard induction to prove the case of powers of 2 and then use the reversed induction principle below to prove for all natural numbers.

Theorem (Reversed Induction Principle)

If a statement P, with a parameter n, is true for an infinite subset of the natural numbers, and if, for every $n > 1$, the truth of P for n implies its truth for $n - 1$, then P is true for all natural numbers.

Arithmetic vs. Geometric Mean (cont.)

- For all powers of 2, i.e., $n = 2^k$, $k \geq 1$: by induction on k.
- Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides ....

Arithmetic vs. Geometric Mean (cont.)

- For all powers of 2, i.e., $n = 2^k$, $k \geq 1$: by induction on k.
- Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides . . ..
- Inductive step:

$$\left(x_1 x_2 \cdots x_{2^{k+1}} \right)^{\frac{1}{2^{k+1}}}$$

Arithmetic vs. Geometric Mean (cont.)

- For all powers of 2, i.e., $n = 2^k$, $k \geq 1$: by induction on k.
- Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides ....
- Inductive step:

$$
(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^{k+1}}}
$$
$$
= \ [(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}}
$$

Arithmetic vs. Geometric Mean (cont.)

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- Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides ....
- Inductive step:

$$(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^{k+1}}}$$
$$= \ [(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}}$$
$$= \ [(x_1 x_2 \cdots x_{2^k})^{\frac{1}{2^k}} (x_{2^k+1} x_{2^k+2} \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}}$$

Arithmetic vs. Geometric Mean (cont.)

🔵 For all powers of 2, i.e., $n = 2^k$, $k \geq 1$: by induction on k.

🔵 Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides ....

🔵 Inductive step:

$$(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^{k+1}}}$$

$$= [(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}}$$

$$= [(x_1 x_2 \cdots x_{2^k})^{\frac{1}{2^k}} (x_{2^k+1} x_{2^k+2} \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}}$$

$$\leq \frac{(x_1 x_2 \cdots x_{2^k})^{\frac{1}{2^k}} + (x_{2^k+1} x_{2^k+2} \cdots x_{2^{k+1}})^{\frac{1}{2^k}}}{2}, \text{ from the base case}$$

Arithmetic vs. Geometric Mean (cont.)

- For all powers of 2, i.e., $n = 2^k$, $k \geq 1$: by induction on k.
- Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides ....
- Inductive step:

$$(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^{k+1}}}$$

$$= \left[(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^k}} \right]^{\frac{1}{2}}$$

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$$\leq \frac{(x_1 x_2 \cdots x_{2^k})^{\frac{1}{2^k}} + (x_{2^k+1} x_{2^k+2} \cdots x_{2^{k+1}})^{\frac{1}{2^k}}}{2}, \text{ from the base case}$$

$$\leq \frac{\frac{x_1 + x_2 + \cdots + x_{2^k}}{2^k} + \frac{x_{2^k+1} + x_{2^k+2} + \cdots + x_{2^{k+1}}}{2^k}}{2}, \text{ from the Ind. Hypo.}$$

Arithmetic vs. Geometric Mean (cont.)

- For all powers of 2, i.e., $n = 2^k$, $k \geq 1$: by induction on k.
- Base case: $(x_1 x_2)^{\frac{1}{2}} \leq \frac{x_1 + x_2}{2}$, squaring both sides ....
- Inductive step:

$$
\begin{aligned}
& (x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^{k+1}}} \\
= \ & [(x_1 x_2 \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}} \\
= \ & [(x_1 x_2 \cdots x_{2^k})^{\frac{1}{2^k}} (x_{2^k+1} x_{2^k+2} \cdots x_{2^{k+1}})^{\frac{1}{2^k}}]^{\frac{1}{2}} \\
\leq \ & \frac{(x_1 x_2 \cdots x_{2^k})^{\frac{1}{2^k}} + (x_{2^k+1} x_{2^k+2} \cdots x_{2^{k+1}})^{\frac{1}{2^k}}}{2}, \text{ from the base case} \\
\leq \ & \frac{\frac{x_1 + x_2 + \cdots + x_{2^k}}{2^k} + \frac{x_{2^k+1} + x_{2^k+2} + \cdots + x_{2^{k+1}}}{2^k}}{2}, \text{ from the Ind. Hypo.} \\
= \ & \frac{x_1 + x_2 + \cdots + x_{2^{k+1}}}{2^{k+1}}
\end{aligned}
$$

Arithmetic vs. Geometric Mean (cont.)

🌐 For all natural numbers: by reversed induction on n.

🌐 Base case: the theorem holds for all powers of 2.

Arithmetic vs. Geometric Mean (cont.)

🔵 For all natural numbers: by reversed induction on n.

🔵 Base case: the theorem holds for all powers of 2.

🔵 Inductive step: observe that

$$\frac{x_1 + x_2 + \cdots + x_{n-1}}{n-1} = \frac{x_1 + x_2 + \cdots + x_{n-1} + \frac{x_1+x_2+\cdots+x_{n-1}}{n-1}}{n}.$$

Arithmetic vs. Geometric Mean (cont.)

$$\left(x_1 x_2 \cdots x_{n-1}\left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)\right)^{\frac{1}{n}} \leq \frac{x_1+x_2+\cdots+x_{n-1}+\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}}{n}$$

(from the Ind. Hypo.)

$$(x_1 x_2 \cdots x_{n-1} \left(\frac{x_1 + x_2 + \cdots + x_{n-1}}{n-1} \right))^{\frac{1}{n}} \quad \leq \quad \frac{x_1 + x_2 + \cdots + x_{n-1} + \frac{x_1 + x_2 + \cdots + x_{n-1}}{n-1}}{n}$$

$$\text{(from the Ind. Hypo.)}$$

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$$\text{(from the Ind. Hypo.)}$$

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$$\left(x_1 x_2 \cdots x_{n-1}\left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)\right) \leq \left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)^n$$

Arithmetic vs. Geometric Mean (cont.)

$$\left(x_1 x_2 \cdots x_{n-1}\left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)\right)^{\frac{1}{n}} \leq \frac{x_1+x_2+\cdots+x_{n-1}+\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}}{n}$$

(from the Ind. Hypo.)

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$$
\begin{aligned}
\left(x_1 x_2 \cdots x_{n-1}\left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)\right)^{\frac{1}{n}} &\leq \frac{x_1+x_2+\cdots+x_{n-1}+\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}}{n} \\
&\qquad \text{(from the Ind. Hypo.)} \\
\left(x_1 x_2 \cdots x_{n-1}\left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)\right)^{\frac{1}{n}} &\leq \frac{x_1+x_2+\cdots+x_{n-1}}{n-1} \\
\left(x_1 x_2 \cdots x_{n-1}\left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)\right) &\leq \left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)^n \\
\left(x_1 x_2 \cdots x_{n-1}\right) &\leq \left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)^{n-1} \\
\left(x_1 x_2 \cdots x_{n-1}\right)^{\frac{1}{n-1}} &\leq \left(\frac{x_1+x_2+\cdots+x_{n-1}}{n-1}\right)
\end{aligned}
$$

Loop Invariants

- An *invariant* at some point of a program is an assertion that holds whenever execution of the program reaches that point.
- Invariants are a bridge between the static text of a program and its dynamic computation.

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- An *invariant* at some point of a program is an assertion that holds whenever execution of the program reaches that point.

- Invariants are a bridge between the static text of a program and its dynamic computation.

- An invariant at the front of a while loop is called a *loop invariant* of the while loop.

- A loop invariant is formally established by induction.
    - Base case: the assertion holds right before the loop starts.
    - Inductive step: assuming the assertion holds before the i-th iteration ($i \geq 1$), it holds again after the iteration.

Number Conversion

Algorithm

Algorithm Convert_to_Binary(n);
begin
    $t := n$;
    $k := 0$;
    while $t > 0$ **do**
        $k := k + 1$;
        $b[k] := t \bmod 2$;
        $t := t \ div \ 2$;
end

Theorem (2.14)

When Algorithm Convert_to_Binary terminates, the binary representation of n is stored in the array b.

Lemma

If m is the integer represented by the binary array b[1..k], then $n = t \cdot 2^k + m$ is a loop invariant of the while loop.

See separate handout for a detailed proof.