EECS 340: Assignment 1

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1 Problem 1

1.1 (a)

Without loss of generality, assume $x > y$ for $x, y \in \mathbb{Z}^+$. The loop invariant is:

$$Euclidean(x, y) = Euclidean(x - y, y) \tag{1}$$

1.2 (b)

Without loss of generality, assume $x > y$ for $x, y \in \mathbb{Z}^+$.

Let d for $d \in \mathbb{Z}^+$ being the greatest common divisor of x and y, a.k.a $d = gcd(x, y)$. As d being a divisor of both x and y, we may therefore have $x = kd$ and $y = jd$ for $k, j \in \mathbb{Z}^+$. Then we may infer:

$$x - y = dk - dj = d(k - j) \tag{2}$$

From *Equation 2* and the known fact that $y = jd$, we may say that d is also a common divisor of $x - y$ and y. By the defination of gcd, this means the upper bound of d cannot be greater than $gcd(x - y, y)$. Thus we may conclude:

$$\begin{aligned} gcd(x, y) &= d \leq gcd(x - y, y) \\ \Rightarrow gcd(x, y) &\leq gcd(x - y, y) \end{aligned} \tag{3}$$

Now similarly, Let e for $e \in \mathbb{Z}^+$ being the greatest common divisor of $x - y$ and y. We may therefore have $x - y = le$ and $y = me$ for $l, m \in \mathbb{Z}^+$. Then we may infer:

$$x = (x - y) + y = le + me = e(l + m) \tag{4}$$

From *Equation 4* and the known fact that $y = me$, we may say that e is also a common divisor of x and y. By the defination of gcd, this means the upper bound of e cannot be greater than $gcd(x, y)$. Thus we may conclude:

$$\begin{aligned} & gcd(x-y, y) = e \leq gcd(x, y) \\ & \Rightarrow gcd(x-y, y) \leq gcd(x, y) \end{aligned} \tag{5}$$

By observing *Equation 3* and *Equation 5*, we may have a constraint of $gcd(x, y) = gcd(x-y, y)$. As the given method $Euclidean()$ is a gcd finder, we may promote such constraint to $Euclidean(x, y) = Euclidean(x-y, y)$ due to the equivalency of $Euclidean(a, b)$ and $gcd(a, b)$.

1.3 (c)

The `while` loop always terminates as the condition $x = y$ will eventually be reached. Due to the fact that we have x and y for $x, y \in \mathbb{Z}^+$; without loss of generality, we assume $x > y$, therefore we must have $x' = x - y$ for $x' \in \mathbb{Z}^+$.

As we have only a finte amount of x', x'', x'''... to decrease for x', x'', and $x''' \in \mathbb{Z}^+$, the decremental calculation of $x_{k+1} = x_k - y_k$[1] will eventually reaches a condition where $x = y$ due to the "well ordering" nature of the natural numbers. Thus, the `while` loop always terminates.

1.4 (d)

In **Section 1.2**, we have proven that $gcd(x, y) = gcd(x-y, y) \Rightarrow Euclidean(x, y) = Euclidean(x-y, y)$ assuming $x > y$ for $x, y \in \mathbb{Z}^+$. Following the principle of induction, we can generalize it as:

$$\begin{gathered} Euclidean(x_k, y_k) = Euclidean(x_{k+1}, y_{k+1}) \\ \text{for } x', y' \in \mathbb{Z}^+ \text{ while} \\ x_{k+1} = x_k - y_k,\ y_{k+1} = y_k \quad \text{if } x_k > y_k \\ y_{k+1} = y_k - x_k,\ x_{k+1} = x_k \quad \text{if } y_k > x_k \end{gathered} \tag{6}$$

Where $Euclidean(x_{k+1}, y_{k+1})$ is the greatest common divisor of (x, y).

As we haven proven in **Section 1.2**, that the `while` loop within the $Euclidean()$ method must terminate. Combined such finding with *Equation 6*, we must also have a:

$$\begin{gathered} Euclidean(a, b) = Euclidean(a_k, b_k) = Euclidean(a_{k+1}, b_{k+1}) = ... \\ ... = Euclidean(a_{k+n}, b_{k+n}) = Euclidean(a_{k+n}, a_{k+n}) \end{gathered} \tag{7}$$

As we know by calculation that $Euclidean(a_{k+n}, a_{k+n}) = a_{k+n}$, a_{k+n}, this will be the greatest common divisor of $Euclidean(a, b)$.

[1] for k being the numbers of iteration went through in the `while` loop.

2 Problem 2

2.1 (a)

Algorithm 1 TwoSum(A, B, n, x) with two pointers

procedure
  $j \leftarrow n - 1$
  $i \leftarrow 0$
  while $i < n$ **and** $j \geq 0$ **do**
    if $A[i] + B[j] < x$ **then**
      $i \leftarrow i + 1$
    else if $A[i] + B[j] > x$ **then**
      $j \leftarrow j - 1$
    else
      return i, j
  return $False$

2.2 (b)

The following is graphical demenstration of *TwoSum(A, B, 5, 12)*:

A

$0(i)$	1	2	3	4
1	3	5	7	9

0	$1(i)$	2	3	4
1	3	5	7	9

0	$1(i)$	2	3	4
1	3	5	7	9

0	1	$2(i)$	3	4
1	3	5	7	9

B

0	1	2	3	$4(j)$
2	4	6	7	10

0	1	2	3	$4(j)$
2	4	6	7	10

0	1	2	$3(j)$	4
2	4	6	7	10

0	1	2	$3(j)$	4
2	4	6	7	10

Thus we have $A[i] + B[j] = 12$ for (i, j) being $(2, 3)$.

2.3 (c)

2.3.1 Loop invariant

To enter the `while` loop with indexes i, j, it is impossible to have any combination of (a, b) where $a \in \{A[0], A[1], ..., A[i-1]\}$ and $b \in \{B[j+1], B[j+2], ..., B[n-1]\}$ to be $a + b = x$.

2.3.2 Initialization

The loop invariant is held true during the initialization, since for $i = 0$ and $j = n - 1$, we must have $a = \emptyset$ and $b = \emptyset$. Thus, it is impossible to have a combination of (a, b) to be $a + b = x$.

2.3.3 Maintenance

Due to the sorted nature of array A, B, we must have:

$$\underbrace{A[0] \le A[1] \le ... \le A[i-1]}_{a} \le A[i] \quad \Rightarrow a \le A[i] \tag{8}$$

$$\underbrace{B[n-1] \ge ... \ge B[j+2] \ge B[j+1]}_{b} \ge B[j] \quad \Rightarrow b \ge B[j] \tag{9}$$

Assume we get $A[i] + B[j] = k$ within an iteration of the `while` loop, we either have $k < x$ or $k > x$. In both cases, we may confidently say that there will be no $a + b = k$. As the index of a must be smaller than i and the index of b must be greater than j. Thus, if there is any $a + b = x$, such loop would have been terminated immediately and we should not be able to reach to indexes i, j in the `while` loop. Therefore, as we are now at the i, j iteration of the `while` loop, this suggests there is no (a, b) combination where $a + b = x$. By this, the loop invariant is held true for all cases within the `while` loop.

Then, to proceed the loop, we may infer the following from *Equation 8* and *9*:

$$\text{if } k < x: \; a + B[j] \le A[i] + B[j] = k \quad \Rightarrow a + B[j] < x \tag{10}$$

$$\text{if } k > x: \; A[i] + b \ge A[i] + B[j] = k \quad \Rightarrow A[i] + b > x \tag{11}$$

As there is no (a, b) combination available to form a x, we must increse the value of index i in the case of $k < x$ to achieve a hopefully greather k' in the next interation; and similarly, to decrese the value of index j to achieve a hopefully lesser k' in the next interation. Thus, the conditional statements in the pseudocode in **Section 2.1** are justified.

2.4 (d)

The worst case of this algorithm is when it returns `False`. In such case we will have i and j traveling the entire bound of $\mathbb{Z}^+ \in [0, n)$. The loop will execute $2n$ times, thus the run time is $O(n)$.

3 Problem 3

3.1 Describe the process using a loop: Pseudocode

Algorithm 2 Kepler442b(m, n)

procedure
  $l \leftarrow m$
  $p \leftarrow n$
  while $(l + p) > 1$ **do**
    Let two individuals fight each other.
    if Both individuals are Lydians **then**
      $l \leftarrow l - 1$
    else if Both individuals are Pisidians **then**
      $p \leftarrow p - 2$
      $l \leftarrow l + 1$
    else
      $l \leftarrow l - 1$
  return l, p

3.2 Define loop invariant and termination

At the start of the k^{th} iteration of the `while` loop, we must have

$$l + p = m + n - (k - 1) \tag{12}$$

$$p \bmod 2 = n \bmod 2 \tag{13}$$

When the `while` loop terminates at $l + p = 1$ there can only be two cases:

$$l = 1,\ p = 0 \quad (n \bmod 2 = 0) \tag{14}$$

$$l = 0,\ p = 1 \quad (n \bmod 2 = 1) \tag{15}$$

Thus, we may infer that if n is odd, a *Pisidian* shall remain. Otherwise if n is even, a *Lydian* shall remain.

3.3 Proof of loop invariant

3.3.1 Initialization

At the beginning it is known that $k = 1$ and $b = n$, thus we may have:

$$l + p = m + n - (k - 1) = l + p = m + n - (1 - 1) \Rightarrow l + p = m + n \tag{16}$$

$$p \bmod 2 = n \bmod 2 \tag{17}$$

As the above two *Equations* satisfy the assumption of the loop invariant, we may say that the scenario of $k = 1$ is true.

3.3.2 Maintenance

Case 1 As it is known that $l+p = (l-1)+p$ and $k = k+1$, we may conclude that $l+p+k$ must remain the same.

Case 2 As it is known that $l + p = (l + 1) + (p - 2)$ and $k = k + 1$, we may conclude that $l + p + k$ must remain the same.

Case 3 As it is known that $l+p = (l-1)+p$ and $k = k+1$, we may conclude that $l+p+k$ must remain the same.

As all three cases satisfy the loop invariant of the algorithm, the induction is therefore proven to be valid.