EECS 340: Assignment 1

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1 Problem 1

1.1 (a)

With $gcd(a, b)$ giving the greatest common divisor of (a, b), the loop invariant is:

$$gcd(a, b) = gcd(x, y) \quad (1)$$
$$\text{for } a, b, x, y \in \mathbb{Z}^+$$

1.2 (b)

1.2.1 Initialization

The loop invariant is held true during initialization of the `while` loop as we defined $x = a$ and $y = b$ in the algorithm, thus *Equation 1* is perserved.

1.2.2 Maintenance

Assume we had x, y in the previous iteration, for this iteration we shall have x', y'. Without loss of generality, assume $x > y$, we must have the following according to the algorithm:

$$x' = x - y$$
$$y' = x$$

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:

$$x - y = dk - dj = d(k - j) \quad (2)$$

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 conclude $gcd(x,y) = gcd(x-y,y)$. As we have discovered $x' = x-y$ and $y' = y$ earlier in this section, this means $gcd(x,y) = gcd(x-y,y) = gcd(x',y')$. Thus, the loop invariant is held true during the maintenance of the `while` loop.

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 $x' = x - y$ and for $x' \in \mathbb{Z}^+$.

As we have only a finte amount of x', x'', x'''... to decrease in the bound of $\mathbb{Z}^+ \in [0, x]$, 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 $gcd(x,y) = gcd(x-y,y)$ assuming $x > y$ for $x, y \in \mathbb{Z}^+$. Following the principle of induction, we can generalize it as:

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

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

As we have proven in **Section 1.2**, that the `while` loop within the algorithm must terminate. Combined such finding with *Equation 6*, we must also have a:

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

As we known by calculation that $gcd(a_{k+n}, a_{k+n}) = a_{k+n}$, thus, a_{k+n} will be the greatest common divisor of (a, b). As the induction performed in *Equation 7* according to constraints defined in *Equation 6* is an exact mathematical mimic of the iterations of the given `Euclidean` algorithm, we may conclude that `Euclidean(a, b)` returns $gcd(a, b)$.

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:

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

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

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*:

$$\text{if } k < x: \; a + B[j] \leq A[i] + B[j] = k \quad \Rightarrow a + B[j] < x \tag{10}$$
$$\text{if } k > x: \; A[i] + b \geq A[i] + B[j] = k \quad \Rightarrow A[i] + b > x \tag{11}$$

As there is no (a, b) combination available to form $a + b = x$, we must increase the value of index i in the case of $k < x$ to achieve a hopefully greater k' in the next iteration; and similarly, to decrease the value of index j to achieve a hopefully lesser k' in the case of $k > x$. Thus, the conditional statements in the pseudocode in **Section 2.1** are justified, and the algorithm is proven to be correct.

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 $\Theta(n)$.

3 Problem 3

3.1 Describe the process using a loop: Pseudocode

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:

$$l = 1,\; p = 0 \;\; (n \bmod 2 = 0) \tag{14}$$
$$l = 0,\; p = 1 \;\; (n \bmod 2 = 1) \tag{15}$$

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

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

3.3 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.