1. **[5 marks] Short answer.** You do **not** need to show your work for any part of this question.

(a) [**1 mark**] Consider a predicate $P(n)$, where $n \in \mathbb{N}$, and suppose that you have proven that $P(1)$ is True, and also that $\forall k \in \mathbb{N}, P(k) \Rightarrow P(3k)$.
Put an "X" in the box next to **each** statement below that you can conclude to be True.

Solution

[X] $P(3)$ [ ] $P(4)$ [ ] $P(5)$ [ ] $P(6)$ [ ] $P(7)$ [ ] $P(8)$ [X] $P(9)$

(b) [**1 mark**] Consider the natural number n whose decimal representation is $(11)_{10}$.
Put an "X" in the box next to **each** correct statement below.

Solution

[ ] $n = (0110)_2$ [X] $n = (1011)_2$ [X] $n = (102)_3$ [ ] $n = (101)_6$

(c) [**1 mark**] Put an "X" in the box next to **each** correct statement below about functions $f, g : \mathbb{N} \to \mathbb{R}^{\geq 0}$ where:

$$f(n) = n + 165 \qquad \text{and} \qquad g(n) = 148n^3$$

Solution

[X] f is eventually dominated by g [ ] g is eventually dominated by f

[ ] f is dominated by g up to a constant factor   [ ] g is dominated by f up to a constant factor

[ ] $f \in \Omega(g)$ [X] $g \in \Omega(f)$

(d) [**1 mark**] Let $RT_f(n) : \mathbb{N} \to \mathbb{R}^{\geq 0}$ be the running time function of the following algorithm.

```python
def f(n: int) -> None:
    """Precondition: n >= 0."""
    i = 1
    while i < n:
        i = i + 2
```

Put an "X" in the box next to **each** correct statement below.

Solution

[ ] $RT_f(n) \in \mathcal{O}(1)$ [X] $RT_f(n) \in \Theta(n)$

[X] $RT_f(n) \in \mathcal{O}(n)$ [X] $RT_f(n) \in \mathcal{O}(n^2)$

(e) [**1 mark**] Let S be a non-empty finite set of real numbers, and let $m \in \mathbb{R}$.
Put an "X" in the box next to the expression below that is equivalent to the English statement "m is an upper bound on the minimum value of S"?

Solution

☐ $\forall x \in S, x \leq m$ ☒ $\exists x \in S, x \leq m$ ☐ $\forall x \in S, m \leq x$ ☐ $\exists x \in S, m \leq x$

2. **[5 marks] Induction.**

Prove the following statement using induction.

$$\forall n \in \mathbb{N},\ (n \geq 1) \Rightarrow \left(\prod_{i=1}^{n}\left(1+\frac{1}{i}\right) = (n+1)\right)$$

<u>Solution</u>

Note: This solution is wordier than expected and provides more intermediate steps than some might find necessary.

Proof. **<u>Base case</u>**: Let $n = 1$. Then

$$\begin{aligned}
\prod_{i=1}^{n}\left(1+\frac{1}{i}\right) &= \prod_{i=1}^{1}\left(1+\frac{1}{i}\right)\\
&= \left(1+\frac{1}{1}\right)\\
&= 2\\
&= (1+1)\\
&= (n+1),
\end{aligned}$$

as required. The base case is satisfied.

(Or take a 'compute left hand side', 'compute right hand side' approach, and compare.)

<u>Induction step</u>: Let $k \in \mathbb{N}$, and assume that $k \geq 1$ and $\prod_{i=1}^{k}\left(1+\frac{1}{i}\right) = (k+1)$. We'll prove that $\prod_{i=1}^{k+1}\left(1+\frac{1}{i}\right) = \big((k+1)+1\big)$.

We have:

$$\begin{aligned}
\prod_{i=1}^{k+1}\left(1+\frac{1}{i}\right) &= \left(\prod_{i=1}^{k}\left(1+\frac{1}{i}\right)\right)\cdot\left(1+\frac{1}{(k+1)}\right)\\
&= \big((k+1)\big)\cdot\left(1+\frac{1}{(k+1)}\right) \qquad \text{(by the I.H.)}\\
&= \big((k+1)\big)\cdot\left(\frac{(k+1)+1}{(k+1)}\right)\\
&= \big((k+1)\big)\cdot\left(\frac{k+2}{k+1}\right)\\
&= (k+2)
\end{aligned}$$

$$= ((k+1)+1),$$

as required. $\square$

3. **[5 marks] Asymptotic analysis.**

In this question, refer to the following definition:

$$g \in \Omega(f): \quad \exists c, n_0 \in \mathbb{R}^+,\ \forall n \in \mathbb{N},\ n \geq n_0 \Rightarrow g(n) \geq c \cdot f(n), \quad \text{where } f, g : \mathbb{N} \to \mathbb{R}^{\geq 0}$$

Prove or disprove the following statement, using only the definition of Ω:

$$\forall f, g : \mathbb{N} \to \mathbb{R}^{\geq 0},\ \Big(\big(\forall n \in \mathbb{N},\ n \geq 207 \Rightarrow g(n) \geq 4\ n\big) \wedge \big(\forall n \in \mathbb{N},\ n \geq 148 \Rightarrow n \geq 100\ f(n)\big)\Big) \Rightarrow g \in \Omega(f)$$

Solution

Proof. Let f, g be arbitrary functions from $\mathbb{N} \to \mathbb{R}^{\geq 0}$.

Assume $\forall n \in \mathbb{N}, n \geq 207 \Rightarrow g(n) \geq 4\ n$ and $\forall n \in \mathbb{N}, n \geq 148 \Rightarrow n \geq 100\ f(n)$.

We need to prove $g \in \Omega(f)$.

That is, we need to prove $\exists c, n_0 \in \mathbb{R}^+,\ \forall n \in \mathbb{N},\ n \geq n_0 \Rightarrow g(n) \geq c \cdot f(n)$

Let $c = 400$ and $n_0 = 207$. (Any $c \leq 400$ or $n_0 \geq 207$ work too.)

Let $n \in \mathbb{N}$ and assume $n \geq n_0$.

Since $n \geq 207$, $g(n) \geq 4\ n$.

Since $n \geq 148$, $n \geq 100\ f(n)$.

Together, we have

$$\begin{aligned} g(n) &\geq 4\ n \\ &\geq 4\ (100\ f(n)) \\ &= 400\ f(n) \\ &= c \cdot f(n), \end{aligned}$$

as required. □

At the marking meeting we decided to give students who attempt a disproof a maxiumum grade of 1 out of 5. They can get 0.5 for showing what statement they want to prove and 0.5 for introducing functions f, g but not much else will be correct.

4. **[10 marks] Running time analysis.**

(a) [**4 marks**] Consider the following algorithm.

```
def f(n: int) -> None:
    """Precondition: n >= 1."""
    i = 1
    while i <= n:              # Loop 1
        j = 0
        while j < n:           # Loop 2
            j = j + (n / i)
        i = i * 2
```

Find the **exact total number of iterations of the Loop 2 body, across all iterations of Loop 1** when `f` is run, in terms of its input n, assuming $n \geq 1$. To simplify your calculations, you may ignore floors and ceilings.

Note: make sure to explain your analysis in English, rather than writing only calculations.

Solution

The values of i executing the Loop 1 body are $i = 1, 2, 4, 8, \ldots,$ up to the last $2^k \leq n$, i.e. $i = 2^0, 2^1, 2^2, \ldots, 2^{\lfloor \log_2 n \rfloor}$ (or just $\log_2 n$ ignoring floors and ceilings).

For each i, the values of j executing the Loop 2 body are $j = 0 \cdot (n/i), 1 \cdot (n/i), 2 \cdot (n/i), 3 \cdot (n/i), \ldots,$ up to just before $n = i \cdot (n/i)$ (trace with a concrete n and some is for intuition), which is (ignoring floors and ceilings) i iterations.

The total is $\displaystyle\sum_{k=0}^{\log_2 n} 2^k = 2^{1+\log_2 n} - 1 = 2n - 1.$

(b) [**6 marks**] Consider the following algorithm, which takes as input a list of nonnegative integers.

```
def alg(A: list[int]) -> None:
    """Precondition: A is a list of nonnegative integers."""
    for i in range(0, len(A)):             # Loop 1
        if A[i] != i:
            for j in range(A[i], len(A)):  # Loop 2
                A[j] = j
            return
```

NOTE: `range(a, b)` is *empty* when `b <= a`.

Prove matching upper (Big-O) and lower (Omega) bounds on the worst-case running time of `alg`, where the size n of the input is the length of the list. Clearly label which part of your solution is a proof of the upper bound, and which part is a proof of the lower bound.

Solution

Upper bound on worst-case running time.

Let $n \in \mathbb{N}$ and `A` be a list of integers of non-negative integers of length n.

Loop 1 iterates no more than n times.

Its body takes 1 step each time, except at most once if the if condition is true in which case it executes Loop 2 and then ends execution.

Loop 2 executes its body $n - \min(A[i], n)$ times (the minimum is for when there are no iterations due to $A[i] \geq n$). This is at most n times since that minimum is non-negative. The body is 1 step each time. Then there is 1 more step for the return which ends the execution.

So the total number of steps is no more than $n \cdot 1 + n \cdot 1 + 1 = 2n + 1 \in \mathcal{O}(n)$.

Lower bound on worst-case running time.

Let $n \in \mathbb{N}$ and $A = [0, 1, 2, \ldots, n-1]$, which is a list of length n containing non-negative integers.

Then each element is equal to its index so the if condition is always false, so Loop 1 iterates to the end taking 1 step each time, for a total number of steps $n \cdot 1 = n \in \Omega(n)$.