Here are several problems that are easy to solve in $O(n)$ time, essentially by brute force. Your task is to design algorithms for these problems that are significantly faster.

1

Suppose we are given an array $A[1..n]$ of n distinct integers, which could be positive, negative, or zero, sorted in increasing order so that $A[1] < A[2] < \cdots < A[n]$.

1.A. Describe a fast algorithm that either computes an index i such that $A[i] = i$ or correctly reports that no such index exists.

Solution: Suppose we define a second array $B[1..n]$ by setting $B[i] = A[i] - i$ for all i. For every index i we have

$$B[i] \;=\; A[i] - i \;\le\; (A[i+1] - 1) - i \;=\; A[i+1] - (i+1) \;=\; B[i+1],$$

so this new array is sorted in increasing order. Clearly, $A[i] = i$ if and only if $B[i] = 0$. So we can find an index i such that $A[i] = i$ by performing a binary search in B. We don't actually need to compute B in advance; instead, whenever the binary search needs to access some value $B[i]$, we can just compute $A[i] - i$ on the fly instead!

Here are two formulations of the resulting algorithm, first recursive (keeping the array A as a global variable), and second iterative.

```
// Return any index i such that ℓ ≤ i ≤ r and A[i] = i
FindMatch(ℓ, r):
  if ℓ > r
    return None
  mid ← (ℓ + r)/2
  if A[mid] = mid            // B[mid] = 0
    return mid
  else if A[mid] < mid       // B[mid] < 0
    return FindMatch(mid + 1, r)
  else                       // B[mid] > 0
    return FindMatch(ℓ, mid − 1)
```

```
FindMatch(A[1..n]):
  hi ← n
  lo ← 1
  while lo ≤ hi
    mid ← (lo + hi)/2
    if A[mid] = mid            // B[mid] = 0
      return mid
    else if A[mid] < mid       // B[mid] < 0
      lo ← mid + 1
    else                       // B[mid] > 0
      hi ← mid − 1
  return None
```

In both formulations, the algorithm ***is*** binary search, so it runs in $O(\log n)$ time.

1.B. Suppose we know in advance that $A[1] > 0$. Describe an even faster algorithm that either computes an index i such that $A[i] = i$ or correctly reports that no such index exists. (**Hint:** This is **really** easy.)

Solution: The following algorithm solves this problem in $O(1)$ time:

```
FindMatchPos(A[1..n]):
  if A[1] = 1
      return 1
  else
      return None
```

Again, the array $B[1..n]$ defined by setting $B[i] = A[i] - i$ is sorted in increasing order. It follows that if $A[1] > 1$ (that is, $B[1] > 0$), then $A[i] > i$ (that is, $B[i] > 0$) for every index i. $A[1]$ cannot be less than 1.

2

Suppose we are given an array $A[1..n]$ such that $A[1] \geq A[2]$ and $A[n-1] \leq A[n]$. We say that an element $A[x]$ is a ***local minimum*** if both $A[x-1] \geq A[x]$ and $A[x] \leq A[x+1]$. For example, there are exactly six local minima in the following array:

9	**7**	7	2	**1**	3	7	5	**4**	7	**3**	**3**	4	8	**6**	9
	▲			▲				▲		▲	▲			▲	

Describe and analyze a fast algorithm that returns the index of one local minimum. For example, given the array above, your algorithm could return the integer 9, because $A[9]$ is a local minimum. (**Hint:** With the given boundary conditions, any array **must** contain at least one local minimum. Why?)

Solution: The following algorithm solves this problem in $O(\log n)$ time:

```
LocalMin(A[1...n]) :
  if n < 100
      find the smallest element in A by brute force
  m ← ⌊n/2⌋
  if A[m] < A[m+1]
      return LocalMin(A[1...m+1])
  else
      return LocalMin(A[m...n])
```

If n is less than 100, then a brute-force search runs in $O(1)$ time. There's nothing special about 100 here; any other constant will do.
Otherwise, if $A[n/2] < A[n/2+1]$, the subarray $A[1 \ldots n/2+1]$ satisfies the precise boundary conditions of the original problem, so the recursion fairy will find local minimum inside that subarray.
Finally, if $A[n/2] > A[n/2+1]$, the subarray $A[n/2 \ldots n]$ satisfies the precise boundary conditions of the original problem, so the recursion fairy will find local minimum inside that subarray.
The running time satisfies the recurrence $T(n) \leq T(\lceil n/2 \rceil + 1) + O(1)$. Except for the $+1$ and the ceiling in the recursive argument, which we can ignore, this is the binary search recurrence, whose solution is $T(n) = O(\log n)$.
Alternatively, we can observe that $\lceil n/2 \rceil + 1 < 2n/3$ when $n \geq 100$, and therefore $T(n) \leq T(2n/3) + O(1)$, which implies $T(n) = O(\log_{3/2} n) = O(\log n)$.

3

Suppose you are given two sorted arrays $A[1..n]$ and $B[1..n]$ containing distinct integers. Describe a fast algorithm to find the median (meaning the nth smallest element) of the union $A \cup B$. For example, given the input

$$A[1..8] = [0, 1, 6, 9, 12, 13, 18, 20] \qquad B[1..8] = [2, 4, 5, 8, 17, 19, 21, 23]$$

your algorithm should return the integer 9. (**Hint:** What can you learn by comparing one element of A with one element of B?)

Solution: The following algorithm solves this problem in $O(\log n)$ time:

```
Median(A[1 .. n], B[1 ... n]) :
if n < 10^100
    use brute force
else if A[n/2] > B[n/2]
    return Median(A[1 .. n/2], B[n/2 + 1 .. n])
else
    return Median(A[n/2 + 1 .. n], B[1 .. n/2])
```

Suppose $A[n/2] > B[n/2]$. Then $A[n/2+1]$ is larger than all n elements in $A[1 \,..\, n/2] \cup B[1 \,..\, n/2]$, and therefore larger than the median of $A \cup B$, so we can discard the upper half of A. Similarly, $B[n/2-1]$ is smaller than all $n+1$ elements of $A[n/2 \,..\, n] \cup B[n/2+1 \,..\, n]$, and therefore smaller than the median of $A \cup B$, so we can discard the lower half of B. Because we discard the same number of elements from each array, the median of the remaining subarrays is the median of the original $A \cup B$.

To think about later:

4 Now suppose you are given two sorted arrays $A[1 \,..\, m]$ and $B[1 \,..\, n]$ and an integer k. Describe a fast algorithm to find the kth smallest element in the union $A \cup B$. For example, given the input

$$A[1 \,..\, 8] = [0, 1, 6, 9, 12, 13, 18, 20] \qquad B[1 \,..\, 5] = [2, 5, 7, 17, 19] \qquad k = 6$$

your algorithm should return the integer 7.

Solution: The following algorithm solves this problem in $O(\log \min\{k, m+n-k\}) = O(\log(m+n))$ time:

```
Select(A[1 .. m], B[1 .. n], k) :
if k < (m + n)/2
    return Median(A[1 .. k], B[1 .. k])
else
    return Median(A[k − n .. m], B[k − m .. n])
```

Here, Median is the algorithm from problem 3 with one minor tweak. If Median wants an entry in either A or B that is outside the bounds of the original arrays, it uses the value $-\infty$ if the index is too low, or ∞ if the index is too high, instead of creating a core dump