Prolegomena unit outline:

- ▶ Algorithms and correctness (**today and next week Monday**)
- ▶ Algorithms and efficiency (next week Friday and Mon, Sept 9)
- ▶ Abstract data types (Wed, Sept 11)
- ▶ Data Structures (Sept 13 and 16)

Today:

- ▶ Bounded linear search problem
- ▶ Check-sorting problem
- ▶ "Binary search" problem

1. The correctness of an algorithm can be verified formally using loop invariants and other proof techniques and empirically using unit tests.

2. The efficiency of an algorithm can be measured formally using algorithmic analysis, big-oh categories, etc, and empirically by running experiments.

	formally		**empirically**
Correctness, verified	by invariants and correctness proofs	*and*	by unit tests
Efficiency, measured	by big-oh categories and related notation	*and*	by experiments

Given a list sequence and a predicate P, return the index of the first element for which the predicate holds, or -1 if none exists. Formally, return

$$-1 \quad \text{if } \forall\, j \in [0, n), \sim P(\texttt{sequence}[j])$$

$$k \quad \text{otherwise, where} \quad P(\texttt{sequence}[k])$$
$$\text{and} \quad \forall\, j \in [0, k), \sim P(\texttt{sequence}[j])$$

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Invariant 1 (Loop of bounded_linear_search.)

(a) $\forall \ j \in [0, \texttt{i} - 1), \sim P(\texttt{sequence}[j])$
(b) found *iff* $P(\texttt{sequence}[\texttt{i} - 1])$
(c) i *is the number of iterations completed.*

> (a) $\forall j \in [0, \mathtt{i} - 1), \sim P(\mathtt{sequence}[j])$
>
> (b) `found` iff $P(\mathtt{sequence}[\mathtt{i} - 1])$
>
> (c) `i` is the number of iterations completed.

Initialization.

(a) Since `i` is initially 0, the range $[0, \mathtt{i}) = [0, 0)$ which is empty. Hence the proposition is vacuously true.

(b) With $\mathtt{i} = 0$, `sequence[i − 1]` doesn't exist. However, it's reasonable to interpret $P(undef)$ as false, which makes this part of the invariant hold.

(c) There have been 0 iterations, and $\mathtt{i} = 0$.

> (a) $\forall\, j \in [0, \mathtt{i} - 1), \sim P(\mathtt{sequence}[j])$
>
> (b) `found` iff $P(\mathtt{sequence}[\mathtt{i} - 1])$
>
> (c) `i` is the number of iterations completed.

Maintenance. Since the variable `i` itself changes during the execution of an iteration, we distinguish between its value when the iteration starts from its value when the iteration finishes by i_{pre} and i_{post}, respectively. Note that $i_{\mathsf{post}} = i_{\mathsf{pre}} + 1$. Similarly distinguish $\mathtt{found}_{\mathsf{pre}}$ and $\mathtt{found}_{\mathsf{post}}$

(a) It must be that $\sim \mathtt{found}_{\mathsf{pre}}$ or else the guard would have failed and the loop would have terminated before this iteration. Thus $\sim P(\mathtt{sequence}[i_{\mathsf{pre}} - 1])$, by the *inductive hypothesis*, part b. Together with the fact that that
$\forall\, j \in [0, i_{\mathsf{pre}} - 1), \sim P(\mathtt{sequence}[j])$, we now have
$\forall\, j \in [0, i_{\mathsf{pre}}), \sim P(\mathtt{sequence}[j])$, that is $\forall\, j \in [0, i_{\mathsf{post}} - 1), \sim P(\mathtt{sequence}[j])$.

(b) Immediate from the assignment to `found`.

(c) Immediate from the update to i. $\qquad\square$

Correctness Claim 1 (bounded_linear_search.)

After at most n iterations, `bounded_linear_search` will return as specified.

Proof. By Invariant 1.c, after at most n iterations, $i = n$ and the guard will fail. Moreover, when the guard fails, either found or $i = n$. Consider the cases of found and $\sim$ found.

Case 1. Suppose found. Then we return $i - 1$. Invariant 1.a tells us that nothing in $[0, i - 1)$ satisfies P. Invariant 1.b tells us that $i - 1$ does. Together these fulfill the second part of the specification: $i - 1$ is the first item satisfying P, and we return it.

Case 2. Suppose $\sim$ found. By elimination $i = n$. Invariant 1.a tells us that nothing in $[0, n - 1)$ satisfies P. Invariant 1.b tells us that $i - 1$, that is, $n - 1$, also does not satisfy P. We return -1, fulfilling the first part of the specification. $\square$

Given a list `sequence` and a total order, determine whether `sequence` is sorted by the given total order.

Given a list `sequence` sorted by a given total order `TO` and given an `item`, return

$$-1 \quad \text{if } \forall \ i \in [0, n), \texttt{sequence}[i] \neq \texttt{item}$$
$$k \quad \text{otherwise, where } \texttt{sequence}[k] = \texttt{item}$$

Given a list sequence sorted by a given total order TO and given an item, return

$$-1 \quad \text{if } \forall \ i \in [0, n), \text{sequence}[i] \neq \text{item}$$
$$k \quad \text{otherwise, where } \text{sequence}[k] = \text{item}$$

Invariant 3 (Loop of binary_search.)

(a) If $\exists \ j \in [0, n)$ such that $\text{item} = \text{sequence}[j]$, then $\exists \ j \in [\text{start}, \text{stop})$ such that $\text{item} = \text{sequence}[j]$.

(b) After i iterations, $\text{stop} - \text{start} \leq \frac{n}{2^i}$.

> (a) If $\exists\, j \in [0, n)$ such that item $=$ sequence[j],
>   then $\exists\, j \in [\text{start}, \text{stop})$ such that item $=$ sequence[j].
> (b) After i iterations, $\text{stop} - \text{start} \leq \frac{n}{2^i}$.

Initialization.

(a) Initially $\text{start} = 0$ and $\text{stop} = n$, so the hypothesis and conclusion are identical.

(b) No iterations yet, so

$$\text{stop} - \text{start} = n - 0 = n = \frac{n}{1} = \frac{n}{2^0}$$

(a) If $\exists\, j \in [0, n)$ such that $\texttt{item} = \texttt{sequence}[j]$,
    then $\exists\, j \in [\texttt{start}, \texttt{stop})$ such that $\texttt{item} = \texttt{sequence}[j]$.

(b) After i iterations, $\texttt{stop} - \texttt{start} \leq \frac{n}{2^i}$.

Maintenance. Distinguish $\texttt{start}_{\textsf{pre}}$ and $\texttt{start}_{\textsf{post}}$, $\texttt{stop}_{\textsf{pre}}$ and $\texttt{stop}_{\textsf{post}}$. Let i be the number of iterations completed. We're given that if $\exists\, j \in [0, n)$ such that $\texttt{item} = \texttt{sequence}[j]$, then $\exists\, j \in [\texttt{start}_{\textsf{pre}}, \texttt{stop}_{\textsf{pre}})$ such that $\texttt{item} = \texttt{sequence}[j]$; also that $\texttt{stop}_{\textsf{pre}} - \texttt{start}_{\textsf{pre}} \leq \frac{n}{2^{i-1}}$ (this is our *inductive hypothesis*). The guard also assures us that $\texttt{stop}_{\textsf{pre}} - \texttt{start}_{\textsf{pre}} > 1$.

We have three possibilities, corresponding to the if-elif-else:

> (a) If $\exists\, j \in [0, n)$ such that $\mathtt{item} = \mathtt{sequence}[j]$,
>   then $\exists\, j \in [\mathtt{start}, \mathtt{stop})$ such that $\mathtt{item} = \mathtt{sequence}[j]$.
>
> (b) After i iterations, $\mathtt{stop} - \mathtt{start} \leq \frac{n}{2^i}$.

Case 1: Suppose $\mathtt{item} < \mathtt{sequence}[\mathtt{mid}]$.

(a) Since sequence is sorted, $\forall\, j \in [\mathtt{mid}, \mathtt{stop_{pre}})$, $\mathtt{item} < \mathtt{sequence}[j]$. Thus if
   $\exists\, j \in [\mathtt{start_{pre}}, \mathtt{stop_{pre}})$, then $\exists\, j \in [\mathtt{start_{pre}}, \mathtt{mid})$, that is (with the update
   to stop but not to start), $\exists\, j \in [\mathtt{start_{post}}, \mathtt{stop_{post}})$
   Now, by transitivity of the conditional, if $\exists\, j \in [0, n)$ such that
   $\mathtt{item} = \mathtt{sequence}[j]$, then $\exists\, j \in [\mathtt{start_{post}}, \mathtt{stop_{post}})$ such that
   $\mathtt{item} = \mathtt{sequence}[j]$.

(b) If the length of the range is odd, then the sub-ranges above and below mid are of
   equal size, each half of the range length minus one. If the range length is even,
   then the lower subrange is half that size and the upper subrange is one less than
   half. Either way we throw away at least half and keep no more than half. So,

$$\mathtt{stop_{post}} - \mathtt{start_{post}} \leq \frac{1}{2} \cdot (\mathtt{stop_{pre}} - \mathtt{start_{pre}}) \leq \frac{1}{2} \cdot \frac{n}{2^{i-1}} \leq \frac{n}{2^i}$$

> (a) If $\exists\, j \in [0, n)$ such that $\texttt{item} = \texttt{sequence}[j]$,
>   then $\exists\, j \in [\texttt{start}, \texttt{stop})$ such that $\texttt{item} = \texttt{sequence}[j]$.
>
> (b) After i iterations, $\texttt{stop} - \texttt{start} \leq \frac{n}{2^i}$.

Case 2: Suppose $\texttt{item} = \texttt{sequence}[\texttt{mid}]$.

(a) Immediately we have $\exists\, j \in [\texttt{mid}, \texttt{mid} + 1)$, and, with the update to $\texttt{stop}$ and $\texttt{start}$, that means $\exists\, j \in [\texttt{start}_{\texttt{post}}, \texttt{stop}_{\texttt{post}})$. Moreover, the conditional is $T \to T \equiv T$.

(b) Note $\texttt{stop}_{\texttt{post}} - \texttt{start}_{\texttt{post}} = 1$. Earlier we said $1 < \texttt{stop}_{\texttt{pre}} - \texttt{start}_{\texttt{pre}} \leq \frac{n}{2^{i-1}}$. Since $\texttt{stop}_{\texttt{pre}} - \texttt{start}_{\texttt{pre}}$ must be a whole number, $2 \leq \frac{n}{2^{i-1}}$, and so $1 \leq \frac{n}{2^i}$. Finally $\texttt{stop}_{\texttt{post}} - \texttt{start}_{\texttt{post}} \leq \frac{n}{2^i}$.

Case 3: Suppose $\texttt{item} > \texttt{sequence}[\texttt{mid}]$. This is similar to Case 1. $\qquad\qquad\square$

Correctness Claim 3 (`binary_search`.)

After at most $\lg n$ *iterations,* `binary_search` *returns as specified.*

Proof. Suppose $i \geq \lg n$. Then $2^i \geq n$ and $\frac{n}{2^i} \leq 1$. Hence $\texttt{stop} - \texttt{start} \leq 1$ and the guard fails.

Invariant 3.a still means that if the item is anywhere, it's in the range. The guard implies that on loop exit the range has size 0 or 1.

Suppose the range has size 0. Then the item isn't in the range (since nothing is), and thus it isn't anywhere. Since $\texttt{stop} = \texttt{start}$, the first part of the conditional fails and and -1 is returned, as specified.

On the other hand, suppose the range has size 1. We still don't know if the item is in the range, but we have only one location to check. If it's in sequence[start], then we return start, which meets the specification. Otherwise the second part of the condition fails and -1 is returned, as specified. $\qquad\square$

Invariant 3 (Loop of binary_search.)

(a) If $\exists\, j \in [0, n)$ such that $\texttt{item} = \texttt{sequence}[j]$, then $\exists\, j \in [\texttt{start}, \texttt{stop})$ such that $\texttt{item} = \texttt{sequence}[j]$.

(b) After i iterations, $\texttt{stop} - \texttt{start} \leq \frac{n}{2^i}$.

Invariant 4 (Preconditions of binary_search_recursive)

(a) If $\exists\, j \in [0, n)$ such that $\texttt{item} = \texttt{sequence}[j]$, then $\exists\, j \in [\texttt{start}, \texttt{stop})$ such that $\texttt{item} = \texttt{sequence}[j]$.

(b) $\texttt{start} \leq \texttt{stop}$

Coming up:

*Do the **pretest** project (due Tuesday, Sept 3—but you can still fix it up)*

*Due **Tues, Sept 4** (end of day)*
Read Section 1.2 (long section—spread it out)
Do Exercises 1.6
Take quiz (algorithms and correctness)