Defensive Programming

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Review

- **Attackers will exploit any and all flaws!**
  - **Buffer overruns, format string usage errors, implicit casting, TOCTTOU, …**
- **Trusted Computing Base (TCB)**
  - **System portion(s) that must operate correctly for system security goals to be assured**

Goals for Today

- **Three principles in crypto design**
  - **Conservative Design, Kerkhoff's Principle, Proactively Study Attacks**
- **Principles for building secure systems**
  - **13 other principles**
  - **Principles are neither necessary nor sufficient to ensure a secure system design, but they are often very helpful**
  - **Goal is to explore what you can do at design time to improve security**

Three Principles in Crypto Design

- **Three principles widely accepted in crypto community that seem useful in computer security**
  - **Conservative Design**
  - **Kerkhoff's Principle**
  - **Proactively Study Attacks**

1. *Conservative Design*

- ***Systems should be evaluated according to worst plausible security failure, under assumptions favorable to attacker***
- **If you find such circumstance where the system can be rendered insecure, then you should seek a more secure system**

2. *Kerkhoff's Principle*

- **Cryptosystems should remain secure even when the attacker knows all internal details of the system**
- **The key should be the only thing that must be kept secret**
- **If your secrets are leaked, it is a lot easier to change the key than to change the algorithm**

3. *Proactively Study Attacks*

- We must devote considerable effort to trying to break our own systems
  - How we can gain confidence in their security
- Other reasons:
  - In security game, attacker gets last move
  - Very costly if a security hole is discovered after wide system deployment
- Pays to try to identify attacks before bad guys find them
  - Gives us lead time to close security holes before they are exploited in the wild

Principles for Secure Systems

- General principles for secure system design
  - Many drawn from a classic 1970s paper by Saltzer and Schroeder
- 1. *Security is Economics*
  - No system is 100% secure against all attacks
    - » Only need to resist a certain level of attack
    - » No point buying a $10K firewall to protect $1K worth of trade secrets
  - Often helpful to quantify level of effort an attacker would expend to break the system.
  - Adi Shamir once wrote, "There are no secure systems, only degrees of insecurity"
    - » A lot of the science of computer security comes in measuring the degree of insecurity

Economics Analogy

- Safes come with a security level rating
- Consumer-grade safe:
  - Rated to resist attack for up to 5 minutes by anyone without tools
- High-end safe might be rated TL-30
  - Secure against burglar with safecracking tools and less than 30 minutes access
  - We can hire security guards with a less than 30 minute response time to any intrusion

Corollary of This Principle

- Focus your energy on securing weakest links
  - Security is like a chain: it is only as secure as the weakest link
  - Attackers follow the path of least resistance, and will attack system at its weakest point
- No point in putting an expensive high-end deadbolt on a screen door
  - Attacker isn't going to bother trying to pick the lock when he can just rip out the screen and step through!

2. *Least Privilege*

- Minimize how much privilege you give each program and system component
  - Only give a program the minimum access privileges it legitimately needs to do its job
- Least privilege is a powerful approach
  - Doesn't reduce failure probability, but can reduce expected cost of failures
- Less privilege a program has, less harm it can do if it goes awry or runs amok
  - Computer-age version of shipbuilder's notion of "watertight compartments":
    - » Even if one compartment is breached, we minimize damage to rest of system's integrity

Principle of Least Privilege Examples

- Can help reduce damage caused by buffer overruns or other program vulnerabilities
  - Intruder gains all the program's privileges
  - Fewer privileges a program has, less harm done if it is compromised
- How is Unix in terms of least privilege?
  - Answer: Pretty lousy!
  - Program gets all privileges of invoking users
  - I edit a file and editor receives all my user account's privileges (read, modify, delete)
- Strictly speaking editor only needs access to file being edited to get job done

Principle of Least Privilege Examples

- **How is Windows in terms of least privilege?**
  - **Answer: Just as lousy!**
  - **Arguably worse, as many users run as Administrator and many Windows programs require Administrator access to run**
- **Every program receives total power over the whole computer!!**
- **Microsoft's security team recognizes this risk**
  - **Advice: Use limited privilege account and "Run As…"**

3. *Use Fail-Safe Defaults*

- **Use *default-deny* polices**
  - **Start by denying all access, then allow only that which has been explicitly permitted**
- **Ensures that if security mechanisms fail or crash, default will be secure behavior**
- **Example: Packet filter is a router**
  - **Failure means no packets will be routed**
    - » **Fail-safe behavior**
  - **Fail-open behavior much more dangerous**
    - » **Attacker just waits for packet filter to crash (or induces crash) and then the fort is wide open!**

Non-Fail-Safe Defaults Examples

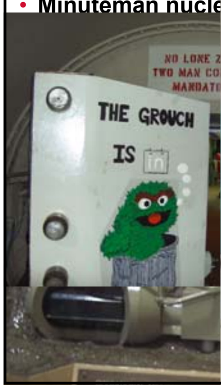
- **SunOS machines used to ship with + in `/etc/hosts.equiv` file**
  - **Allowed anyone with root access on any machine on the Internet to log into your machine as root**
- **Irix machines used to ship with `xhost +` in their X Windows configuration files**
  - **Allowed anyone to connect to Xserver**

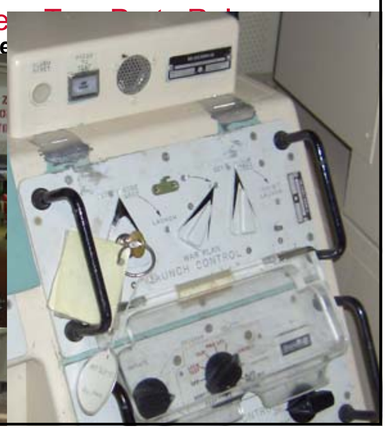
4. *Separation of Responsibility*

- Split up privilege
  - No one person or program has complete power
  - Require more than one party to approve before access is granted
- Two-party rule examples
  - Movie theater: pay teller and get ticket stub, then separate employee tears ticket in half, collects a half of it and puts it in lockbox
    - » Helps prevent insider fraud (under-/over-charge)
  - Most companies: purchases over certain amount must be approved by both requesting employee and a purchasing officer
    - » Helps prevent insider fraud in vendor choice

Nucle

- Minuteman nucle





5. *Defense in Depth*

- A closely related principle
  - "You can recognize a security guru because they're wearing both a belt and a set of suspenders"
- Principle is that with multiple redundant protections, all of them have to be breached to endanger system security

6. *Psychological Acceptability*

- Important that users buy into security model
- Examples
  - Company FW admin capriciously blocks apps that engineers need to get their jobs done
    - They view FW as damage and tunnel around it
  - Sys admin makes all passwords auto-generated long unmemorizable strings changed monthly
    - Users simply write down their passwords on yellow post-its attached to their screens
- No system can remain secure for long when all its users actively seek to subvert it
  - Sys admins aren't going to win this game…
  - Well-intentioned edicts can ultimately turn out to be counter-productive

7. *Usability*

- Security systems must be usable by ordinary people and take into account humans' role
- Example
  - Web browser pops up security warnings, but no indication of steps you should take
    - What do you do? Like everyone else click "OK"…
  - NSA's crypto equipment stores key material on small physical token shaped like ordinary key
    - To activate encryption device, insert key into device's slot and turn it
    - Intuitively understandable interface, even for 18-year-olds soldiers with minimal training

8. *Ensure Complete Mediation*

- When enforcing access control policies, ensure that *every* access to *every* object is checked
- Caching is a slightly sticky subject
  - Can sometimes avoid checking every access and allowing security decisions to be cached, but beware
- What if context relevant to security decision changes, and cache entry isn't invalidated?
  - Someone might get away with accessing something they shouldn't

9. *Least Common Mechanism*

- Be careful with shared code!.
  - Original assumptions may no longer be valid
  - Threat model may have changed
- Example: Internet users were once only researchers, who trusted each other
  - Most networking protocols designed during those days assumed that all other network participants were benign and non-malicious
  - Not true today! Millions of users, many malicious ones…
  - Many old network protocols are suffering under the strain of attack (e.g., spam)

10. *Detect if You Can't Prevent*

- If you can't prevent break-ins, at least detect them and provide a way to identify the perpetrator
- Forensics are important
  - Keep audit logs so you can analyze break-ins afterwards
- Example: FIPS 140-1 federal standard for tamper-resistant hardware
  - Type III devices (highest level) are very expensive
  - Type II devices are only required to be tamper-evident (e.g., a visibly broken seal)
    - Lower cost and usable in broad set of apps

11. *Orthogonal Security*

- Security mechanisms implemented orthogonally (transparently) to rest of system are useful in protecting legacy systems
- Also, allow us to improve assurance by composing multiple mechanisms in series

12. *Don't Rely on Security Through Obscurity*

- **We've seen this one in the last lecture…**
- **'Security through obscurity' phrase**
  - **Systems that rely on secrecy of design, algorithms, or source code to be secure**
- **Claimed reasoning:**
  - **"This system is so obscure, only 100 people understand anything about it, so what are the odds that adversaries will bother attacking it?"**
- **Self-defeating approach**
  - **As system becomes more popular, more incentive to attack it, and cannot rely on its obscurity to keep attackers away…**

Secret Designs

- **Very hard to keep system design secret from a dedicated adversary**
  - **Every running installation has binary executable code that can be disassembled**
  - **Hard to assess chances that secret will leak or difficulty of learning the secret**
- **If secret ever leaks, can be hard to update widely-deployed systems**
  - **No recourse if someone ever succeeds**
- **History has a lousy track record**
  - **Many systems that have relied upon code or design secrecy for security have failed miserably**

13. *Design Security in, From the Start*

- **Often doesn't work to retrofit security into an existing implemented application**
  - **Stuck with chosen architecture**
  - **Can't change system decomposition to ensure any of the good principles we discussed**
- **Backwards compatibility often particularly painful, because you have to support worst insecurities of all previous versions**

Administrivia

Writing Secure Code

- Goal is eliminating *all* security-relevant bugs, no matter how unlikely they are to be triggered in normal execution
  - Intelligent adversary will find abnormal ways to interact with our code
- Different goal from software reliability
  - Focus is on most likely to happen bugs
  - Can ignore obscure condition bugs
- Dealing with malice is much harder than dealing with mischance

Three Fundamental Techniques

- (1) Modularity and decomposition for security
- (2) Formal reasoning about code using invariants
- (3) Defensive programming

- In the next lecture, we'll discuss programming language-specific issues and integrating security into the software lifecycle

Modularity

- Decompose well-designed system into modules
  - All interactions through well-defined interfaces
  - Each module performs a clear function
    - "What functionality it provides" not "how it is implemented"
- Granularity depends on system and language
  - A module typically has state and code
  - In Java (object-oriented), a class (or a few closely related classes)
  - In C, its own file with a clear external interface, along with many internal functions that are not externally visible or callable

Module Design

- Focus on interface design
  - Interface is the caller-callee contract
  - Should change less often than implementation
  - Caller only needs to understand interface
  - Should interact only through defined interface
    - No global variables for communication
- A module is a blob
  - The interface is its surface area
  - The implementation is its volume
  - Thoughtful design has narrow and conceptually clean interfaces and modules have low surface area to volume ratio

Module Decomposition Suggestions

- Minimize the harm caused by module failure
  - Contain damage from module penetration (buffer overrun) or unexpected behavior (implementation bug)
- Draw a security perimeter around each module
  - Keep one misbehaving module from changing other modules' behaviors
- Plan for failure:
  - Think in advance about consequences of each module being compromised
  - Structure system to reduce consequences

Monolithic Architecture

- **All modules in a common address space**
  - **Unecessary security risk: compromise one module and all others can be penetrated**
- **Alternatives:**
  - **Java isolates modules using type-safety**
  - **Languages like C require placing each module in its own process to protect it**
- ***Follow principle of least privilege at a module granularity***
  - **Provide each module with the least privilege necessary to get its job done**
  - **Architect system so most modules need only minimal privileges**

Module Design with Least Privilege

- **Can you structure a complex system of computations that require lots of code so they're isolated in modules with few privileges?**
- **Modules with extra privileges should have very little code**
  - **The more privilege for a module, the greater the confidence we need that it is correct**
  - **More confidence generally requires less code…**

Module Example

- **Break up a network server listening on a port below 1024 into two pieces:**
  - **Small start-up wrapper and the app itself**
  - **Binding to 0 – 1023 port requires root privileges, so let wrapper run as root, bind to desired port, and then spawn the app passing it the bound port**
- **The app itself then runs as non-root user**
  - **Limits damage if app is compromised**
- **Wrapper can be written in a few dozen lines of code making thorough validation possible**

Web Server

- **Composition of two modules**
  - **1. Handles incoming network connections and identifies requested URLs**
    - » **No privileges (root wrapper binds port 80)**
  - **2. Translates URL into filename and reads it from the filesystem**
    - » **Might run as special `www` userid and only documents intended to be publicly visible are readable by user `www`**
- **Defense in Depth/Layered Defense**
  - **Leverage OS's file access controls so that even if second module is penetrated, an attacker can't harm rest of system**

Reasoning About Code

- **Functions make certain assumptions about their arguments**
  - **Caller must make sure assumptions are valid**
  - **These are often called *preconditions***
- **Precondition for `f()` is an assertion (a logical proposition) that must hold at input to `f()`**
  - **Function `f()` must behave correctly if its preconditions are met**
  - **If any precondition is not met, all bets are off**
- **Caller must call `f()` such that preconditions true – an obligation on the caller, and callee may freely assume obligation has been met**

Simple Precondition Example

- ```
  /* Requires: p != NULL */
  int deref(int *p) {
      return *p;
  }
  ```
- **Unsafe to dereference a null pointer**
  - **Impose precondition that caller of `deref()` must meet: *p ≠ NULL* holds at entrance to `deref()`**
- **If all callers ensure this precondition, it will be safe to call `deref()`**
- **Can combine assertions using logical connectives (and, or, implication)**
  - **Also existentially and universally quantified logical formulas**
  ```

Another Example

```
/* Requires:
    a != NULL
    for all j in 0..n-1,  a[j] != NULL */
int sum(int *a[], size_t n) {
    int total = 0, i;
    for (i=0; i<n; i++)
        total += *(a[i]);
    return total;
}
```

- **Second precondition:**
  - **Forall j.(0 ≤ j < n) → a[j]≠NULL**
  - **If you're comfortable with formal logic, write your assertions this way for precision**
- **Not necessary to be so formal**
  - **Goal is to think explicitly about assumptions and communicate requirements to others**

Postconditions

- ***Postcondition* for `f()` is an assertion that holds when `f()` returns**
  - **`f()` has obligation of ensuring condition is true when it returns**
  - **Caller may assume postcondition has been established by `f()`**
- **Example:**

```
/* Ensures: retval != NULL */
void *mymalloc(size_t n) {
    void *p = malloc(n);
    if (!p) {
        perror("Out of memory");
        exit(1);
    }
    return p;
}
```


Process for Writing Function Code

- **First write down its preconditions and postconditions**
  - **Specifies what obligations caller has and what caller is entitled to rely upon**
- **Verify that, no matter how function is called, if precondition is met at function's entrance, then postcondition is guaranteed to hold upon function's return**
  - **Must prove that this is true for all inputs**
  - **Otherwise, you've found a bug in either specification (preconditions/postconditions) or implementation (function code)**

Proving Precondition→Postcondition

- **Basic idea:**
  - **Write down a precondition and postcondition for every line of code**
  - **Apply same sort of reasoning as for function**
- **Requirement:**
  - **Each statement's postcondition must match (imply) precondition of any following statement**
  - **At every point between two statements, write down *invariant* that must be true at that point**
    - **Invariant is postcondition for preceding statement, and precondition for next one**

Example

- **Easy to tell if an isolated statement fits its pre- and post-conditions**
- **Valid postcondition for "`v=0;`" is `v=0` (no matter what the precondition is)**
  - **Or, if precondition for "`v=v+1;`" is `v≥5`, then a valid postcondition is `v≥6`**
- **If precondition for "`v=v+1;`" is `w≤100`, then a valid postcondition is `w≤100`**
  - **Assuming `v` and `w` do not alias**

Loop Invariant

- **An assertion that is true at entrance to the loop, on any path through the code**
  - **Must be true before every loop iteration**
    - **Both a pre- and post-condition for the loop body**
- **Example: Factorial function code**

```
/* Requires: n >= 1 */
int fact(int n) {
    int i, t;
    i = 1;
    t = 1;
    while (i <= n) {
        t *= i;
        i++;
    }
    return t;
}
```

  - **Prerequisite: input must be at least 1 for correctness**
  - **Prove: value of `fact()` is always positive**

Verifying Invariant Correctness

```
/* Requires: n >= 1
   Ensures: retval >= 0 */
int fact(int n) {
    int i, t;          /* n>=1 */
    i = 1;             /* n>=1 && i==1 */
    t = 1;             /* n>=1 && i==1 && t==1 */
    while (i <= n) {
       /* 1<=i && i<=n && t>=1   <-- loop invariant */
       t *= i;          /* 1<=i && i<=n && t>=1 */
       i++;             /* 2<=i && i<=n+1 && t>=1 */
    }                   /* i>n && t>=1 */
    return t;
}
```

- **Easy if we examine each step:**
  - **Function's precondition implies invariant at function body start**
  - **Invariant at end of function body implies function's postcondition**
  - **If each statement matches invariant immediately before and after it, everything's OK**
- **That leaves the loop invariant…**

Verifying the Loop Invariant

- **Loop invariant:** `1<=i && i<=n && t>=1`
- **Prove it is true at start of first loop iteration**
  - **Follows from:**
    - » $n \geq 1 \wedge i=1 \wedge t=1 \rightarrow 1 \leq i \leq n \wedge t \geq 1$
    - » **if** $i=1$**, then certainly** $i \geq 1$
- **Prove that if it holds at start of any loop iteration, then it holds at start of next iteration (if there's one)**
  - **True, since invariant at end of loop body** $2 \leq i \leq n+1 \wedge t \geq 1$ **and loop termination condition** $i \leq n$ **implies invariant at start of loop body** $1 \leq i \leq n \wedge t \geq 1$
- **Follows by induction on number of iterations that loop invariant is always true on entrance to loop body**
  - **Thus,** `fact()` **will always make postcondition true, as precondition is established by its caller**

Another Example: Recursion

```
/* Requires: n >= 1 */
int fact(int n) {
    int t;
    if (n == 1)
        return 1;
    t = fact(n-1);
    t *= n;
    return t;
}
```

- **Do you see how to prove that this code always outputs a positive integer?**

Analysis

- ```
  /* Requires: n >= 1
     Ensures: retval >= 0 */
  int fact(int n) {
      int t;
      if (n == 1)
          return 1;          /* n>=2 */
      t = fact(n-1);        /* t>=0 */
      t *= n;                /* t>=0 */
      return t;
  }
  ```
- **Before recursive call to `fact()`, we know:**
  - **`n`≥`1` (by precondition), `n`≠`1` (since if stmt didn't follow then branch), and `n` is an integer**
  - **Follows that `n`≥`2`, or `n-1`≥`1` (means precondition is met when making recursive call)**
- **Can conclude that `fact(n-1)` return value is positive from postcondition for `fact()`**

Function Post-/Pre-Conditions

- **Any time we see a function call, we have to verify that its precondition will be met**
  - **Then we can conclude its postcondition holds and use this fact in our reasoning**
- **Annotating every function with pre- and post-conditions enables *modular reasoning***
  - **Can verify function `f()` by looking only its code and the annotations on every function `f()` calls**
    - **Can ignore code of all other functions and functions called transitively**
  - **Makes reasoning about `f()` an almost purely local activity**

Documentation

- **Pre-/post-conditions serve as useful documentation**
  - **To invoke Bob's code, Alice only has to look at pre- and post-conditions – she doesn't need to look at or understand his code**
- **Useful way to coordinate activity between multiple programmers:**
  - **Each module assigned to one programmer, and pre-/post-conditions are a contract between caller and callee**
  - **Alice and Bob can negotiate the interface (and responsibilities) between their code at design time**
  ```

Avoiding Security Holes

- To avoid security holes (or program crashes)
  - Some implicit requirements code must meet
    - » Must not divide by zero, make out-of-bounds memory accesses, or deference null ptrs, …
- We can try to prove that code meets these requirements using same style of reasoning
  - Ex: when a pointer is dereferenced, there is an implicit precondition that pointer is non-null and in-bounds

Proving Array Accesses are in-bounds

- ```
  /* Requires: a != NULL and a[] holds n elements */
  int sum(int a[], size_t n) {
      int total = 0, i;
      for (i=0; i<n; i++)
              /* Loop invariant: 0 <= i < n */
          total += a[i];
      return total;
  }
  ```
- Loop invariant true at entrance to first iteration
  - First iteration ensures `i=0`
- It is true at entrance to subsequent iterations
  - Loop termination condition ensures `i<n`, and `i` only increases
- So array access `a[i]` is within bounds

Buffer Overruns

- Proving absence of buffer overruns might be much more difficult
  - Depends on how code is structured
- Instead of structuring your code so that it is hard to provide a proof of no buffer overruns, restructure it to make absence of buffer overruns more evident
- Lots of research into automated theorem provers to try to mathematically prove validity of alleged pre-/post-conditions
  - Or to help infer such invariants
  ```

Pre-/Post-Condition Summary

- Looks tedious, but gets easier over time
  - With practice you can avoid writing down detailed invariants before every statement
    - » Think about data structures and code in terms of invariants first, then write the code
  - Usually can avoid formal notation, omit obvious parts, and only write down important ones
    - » Usually writing down pre-/post-conditions and loop invariant for every loop is enough
- Reasoning about code takes time and energy
  - Worth it for highly secure code

Defensive Programming

- Like defensive driving, but for code:
  - Avoid depending on others, so that if they do something unexpected, you won't crash – survive unexpected behavior
- Software engineering focuses on functionality:
  - Given correct inputs, code produces useful/correct outputs
- Security cares about what happens when program is given invalid or unexpected inputs:
  - Shouldn't crash, cause undesirable side-effects, or produce dangerous outputs for bad inputs
- Defensive programming
  - Apply idea at every interface or security perimeter
    - » So each module remains robust even if all others misbehave
- General strategy
  - Assume attacker controls module's inputs, make sure nothing terrible happens

Defensive Programming

- Write module *M* to provide functionality to a single client
  - *M* should provide useful responses if client provides valid inputs
  - If client provides an invalid input, then *M* is no longer under any obligation to provide useful output
    - » *M* must still protect itself (and rest of system) from being subverted by malicious inputs

Very Simple Example

- `char charAt(char *str, int index) {`
  `return str[index];`
  `}`
- **Function is too fragile!**
  - `charAt(NULL, any)` will cause a crash
  - `charAt(s, i)` causes a buffer overrun if `i` is out-of-bounds (too small or large) for `s`
- **Neither can be easily fixed without changing function's interface**

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Another Simple Example with Many Flaws

```
char *double(char *str) {
    size_t len = strlen(str);
    char *p = malloc(2*len+1);
    strcpy(p, str);
    strcpy(p+len, str);
    return p;
}
```

- `double(NULL)` will cause a crash
  - Fix: test if `str` is a null ptr, and if so, return `NULL`
- Return value of `malloc()` is not checked
  - If out-of-memory, `malloc()` will return null ptr and call to `strcpy()` will cause program crash
  - Fix: test return value of `malloc()`
- If `str` is very long, then expression `2*len+1` will overflow, potentially causing a buffer overrun
  - 2^{31} byte input str on 32-bit machine will have 1 byte allocated, and `strcpy` will immediately trigger a heap overrun

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Trickier Example: Java Sort Routine

- Accepts array of objects that implements `Comparable` interface and sorts them
  - Each object implements `compareTo()` method, and `x.compareTo(y)` must return a negative, zero, or positive integer, depending on whether `x` is less than, equal to, or greater than `y`
- Implementing a defensive sort routine is actually fairly tricky, because a malicious client could supply objects whose `compareTo()` method behaves unexpectedly
  - Calling `x.compareTo(y)` twice might yield two different results (if `x` or `y` are malicious)
  - Or, consider: `x.compareTo(y) == 1`, `y.compareTo(z) == 1`, and `z.compareTo(x) == 1`
- Sort routine might go into an infinite loop or worse

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Some General Advice

- ***1. Check for error conditions***
  - Always check return values of all calls (assuming this is how they indicate errors)
  - In languages with exceptions, can locally handle it or propagate (expose) to caller
  - Check error paths very carefully
    - Often poorly tested, so they often contain memory leaks and other bugs
- **What if you detect an error condition?**
  - For expected errors, try to recover
  - Harder to recover from unexpected errors
  - Always safe to abort processing and terminate if an error condition is signaled (*fail-stop* behavior)