# Secure Software Development

## Defensive Programming

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Winter 2020/21, www.iaik.tugraz.at

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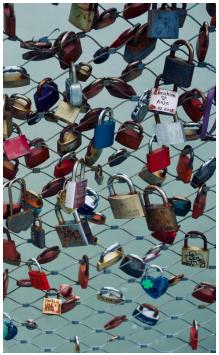
# Defense-in-Depth



- Understand the attacker's perspective
  - *"Know your enemy"* – Sun Tzu, *The Art of War*
- Defend on all layers
  - The weakest link will break first

**Attacker's perspective**

- Vulnerability discovery ☑
- Exploitation ☑
- Privilege elevation ☑

**Defender's perspective**

- Vulnerability prevention (today)
- Exploit prevention (next time)
- Privilege minimization (next time)

## Attacker's perspective

- Vulnerability discovery
  - buffer/integer overflow, use-after-free, format strings, type confusion
- Exploitation
  - Data corruption, shellcode, code reuse, ROP, return-to-libc
- Privilege elevation
  - admin flag, spawn a shell, cat flag.txt, gain persistence

## Defender's perspective

- Vulnerability prevention
  - Code quality, memory safety, type safety, error handling ...
- Exploit prevention
  - Compiler/runtime defenses, hardware defenses
- Privilege minimization
  - System call filtering, sandboxing, virtualization

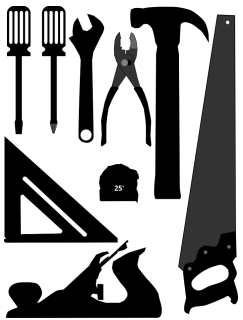
# Vulnerability Prevention: Goals I

- Overall goal: eliminate **all** vulnerabilities
  - Prove the program correct
    - → Other courses, e.g., Model-based Testing, Verification and Testing
      - *"A program is* **functionally** *correct* **iff** *it satisfies the specification"*
  - Specification needed
    - Bugs in spec?
    - Ambiguities?
    - **Unspecified behavior?!**
      - Most vulnerabilities are not specified
    - *"A program is* **safe iff** *it is functionally correct and does not exhibit unspecified behavior"*
    - **Invalid assumptions?!** ~~*"The attacker is not supposed to ..."*~~

# Vulnerability Prevention: Goals II

- Verification is ~~hard~~ super hard
  - seL4 microkernel took 20.5 person years to verify [**?**]
- Overall goal: eliminate as many vulnerabilities as possible
  - Maybe degrade some vulnerabilities to unexploitable bugs
  - Best effort but no hard security guarantee
  - → Defense-in-Depth is necessary, e.g., exploit prevention and privilege minimization
- Practical goal: **Improve code quality** via defensive programming

# Defensive Programming Overview



**Sub-goals**

- Memory safety
- Type safety
- Integer safety
- Secure data flow
  - Input sanitization
- Secure control flow
  - Error handling

**General principles**

- Choose appropriate language
- Improve code quality
  - Coding standard
  - Source code reuse
  - Portability / Assumptions
  - Documentation
  - Testing & Assertions
  - Compiler assistance

- Goal: eliminate array out-of-bounds access
- Use or develop accessor functions which check boundaries
  - Example: C++ std::vector

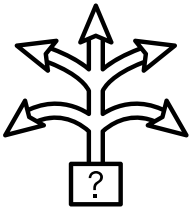
```
int x = vector[index];     // unchecked
int y = vector.at(index); // checked
```

  - Memory-safe languages: Compiler can optimize out unnecessary bounds checks

- 🏁 Goal: eliminate temporal issues
- 👉 Use reference counting
  - Avoids memory leaks and double free
  - E.g., C++ smart pointers `std::shared_ptr`
- 👉 Exclusive ownership: only one owner with write access
  - Avoids race conditions and time-of-check vs time-of-use (TOCTOU)
  - E.g., Rust ownership
- 👉 Deinitialize free'd resources
  - Avoids use-after-free (UAF)

```
memset(ptr, 0, sizeof(*ptr); free(ptr); ptr = NULL;
```

# Type safety




- Goal: eliminate type confusion issues
- Avoid use of C `unions`
- Avoid unsafe casts
  - Avoid cast to `(void*)` This should mainly be used for memory allocators
  - Avoid C++ `reinterpret_cast`


- General concept
- Store additional runtime metadata alongside pointer, e.g.:
  - pointer type
  - length
  - validity
  - access permissions
- Examples: C++ smart pointer, `dynamic_cast<>`

☹ Typically consume 2–5 times more memory per pointer

- Goal 1: prevent integer overflows/underflows
- Use correct integer types
  - Use `size_t` for indices and length
  - Use `uint64_t`, etc. for fixed-size integers
  - Use `uintptr_t` for pointer-to-integer conversion
- For **every** arithmetic operation check if overflow is possible
- Detect and prevent integer overflows via
  - Compiler builtins, e.g. `__builtin_saddl_overflow`
  - Larger types for intermediate results
  - Explicit checks (see next tutorial)

- Goal 2: prevent integer conversion issues
- Avoid mixing `signed` and `unsigned`
  - Attention: `char` can be `signed` or `unsigned`
- Make large types explicit

```
int y = ...;
long long x = y + 2;    // int-addition might overflow
long long x = (long long)y + 2LL;
```

- Perform range checks on each downcast

```
int x = ...;
if (x > SHORT_MAX) error();
short y = (short)x;
```

- Goal 3: prevent undefined behavior
- Know undefined behavior! E.g.,
  - Left-shift a signed type
    - number could become negative if MSB is reached
  - Left-shift by a negative number
  - `sizeof(void*)`
    - GNU C specifies it to be 1

```
size_t strlen(void* string) {
   while(*(char*)string != '\0')
       string++;    // undefined increment
}
```

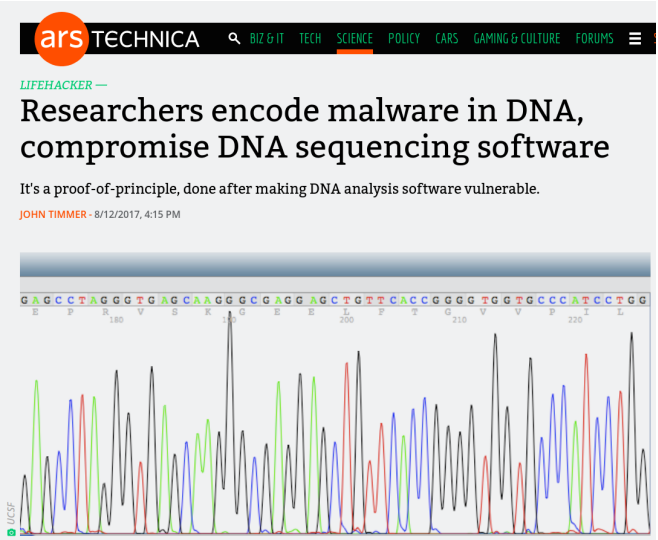
- Observation: Attacker injects payload as data, which might get misinterpreted as code
- Idea: Focus on data flow rather than memory objects, types, etc.
- Goal: Secure data flow → attacker cannot inject payload
  - Check *every* input an attacker can control directly or indirectly
  - Better: Check *every* input.
  - **Input sanitization**

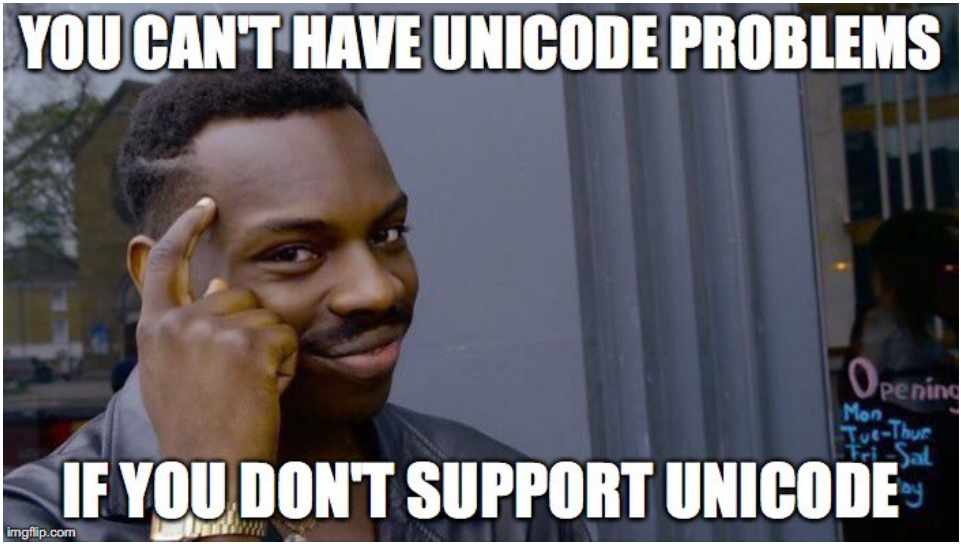

by **Michael Mimoso** Follow @mike_mimoso January 28, 2016 , 9:04 am

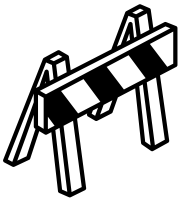
Stepankin said he was able to execute arbitrary shell commands on PayPal servers by taking advantage of insecure Java object deserialization. He wrote in a blog post that he was able to access PayPal's production servers.

"I realized that I could execute arbitrary OS commands on manager.paypal.com web servers and moreover, I could establish a back connection to my own internet server and, for example, upload and execute a backdoor," he wrote. "[As a] result, I could get access to production databases used by manager.paypal.com application."

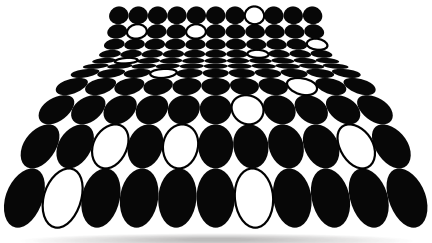
"I just read "/etc/passwd" file by sending it to my server as a proof of the vulnerability," he wrote.


ars TECHNICA
BIZ & IT
TECH
SCIENCE
POLICY
CARS
GAMING & CULTURE
FORUMS
LIFEHACKER —
Researchers encode malware in DNA, compromise DNA sequencing software
It's a proof-of-principle, done after making DNA analysis software vulnerable.
JOHN TIMMER - 8/12/2017, 4:15 PM
VCSF


YOU CAN'T HAVE UNICODE PROBLEMS
IF YOU DON'T SUPPORT UNICODE
imgflip.com



- Goal: sanitize dangerous input
  - Detect and reject
    - Pattern matching
    - Canonicalization
  - Neutralize
    - Filtering
    - Character escaping



- 👉 Use existing sanitizers wherever possible!
  - HTML, SQL, CSS, XML, E-mail ...
- Blacklist (deny list)
  - ☹ It is easy to overlook stuff
- Whitelist (allow list)
  - ☺ Very restrictive, thus secure
  - ☹ Very restrictive, thus often unusable
- Regex
  - ☺ Very powerful
  - ☹ Horrible syntax
- Rust pattern matcher


Issue: equivalent representations make sanitization a pain

Example: equivalent Unix paths

```
/proc/self/maps
~/../../proc/self/maps
/proc/1/maps
/proc/1/./maps
/proc/1/./////maps
/proc/../proc/1/maps
...
```

Example: equivalent numbers

```
21
21.0
+21
025
0x15
21e0
...
```


- Idea: make parsing more uniform
- Canonicalization before Sanitization!
- Example: canonicalizing paths using `realpath`
  - Resolve relative paths

    `../../etc/passwd --> /etc/passwd --> DENY`

    `./etc/passwd --> /home/ssd/etc/passwd --> ALLOW`
  - Resolve symlinks:

    `mylink-to-passwd --> /etc/passwd --> DENY`


More issues to consider

- Newlines: `\r\n` vs. `\n`
- Path separators: Windows \ vs. Unix /
- Case (in)sensitivity: (Git CVE-2014-9390)
- File system permissions: FAT vs NTFS vs EXT
- Time stamps (UTC vs GMT)

- Issue: user input gets interpreted as code, e.g.:
  - SQL injection
  - Cross-site scripting (HTML injection)
  - Shell command injection

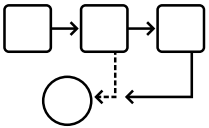
```
Please enter your username: Dr.`whoami`
User Dr.Weiser created.
```

- Best idea: never interpret user input as code!
- If not possible: neutralize dangerous characters
- Escaping before Interpretation!

- Examples:
  - Shell: replace `'` with `\'`
  - HTML: replace `<script>` with `&lt;script&gt;`

Do not reinvent escaping!

Use existing libraries



- Return error codes
- Exception handling
- Goto

```
1  FILE* f = fopen("report.log", "a");
2  fprintf(f, "Server started\n");
3  printf("DEBUG: we're running\n");
4  fclose(f);
```

- Always check for error codes (line 1 & 2)
- Exemptions (line 3 & 4)
  - If there's nothing you can do in case of an error
  - In particular cleanup routines `fclose`, `munmap`, (`free`)

Better now?

```
1  FILE* f = fopen("report.log", "a");
2  if (NULL == f) { perror("Unable to open file"); return; }
3  assert(0 > fprintf(f, "Server started\n"));
4  printf("DEBUG: we're running\n");
5  fclose(f);
```

- Compiler might optimize out `asserts` (line 3)
  - `fprintf` is never executed!
  - Compile flag `-DNDEBUG`
- Never use `assert` to check for actual error codes

```
1  char* tmp = realloc(buffer, newsize);
2  if (NULL == tmp) { return REALLOC_FAILED; }
```

What if `newsize` is 0?

> The realloc() function returns a pointer to the newly allocated memory, which is suitably aligned for any built-in type and may be different from ptr, or NULL if the request fails. If size was equal to 0, either NULL or a pointer suitable to be passed to free() is returned. If realloc() fails, the original block is left untouched; it is not freed or moved.

- Consider all possible error combinations

```
1  char* tmp = realloc(buffer, newsize);
2  if (NULL == tmp && newsize > 0) { return REALLOC_FAILED; }
```

- Make sure your own functions return proper error codes

***RETURN VALUE***

If successful, the *pthread_create*() function shall return zero; otherwise, an error number shall be returned to indicate the error.

***ERRORS***

The *pthread_create*() function shall fail if:

[EAGAIN]
The system lacked the necessary resources to create another thread, or the system-imposed limit on the total number of threads in a process {PTHREAD_THREADS_MAX} would be exceeded.
[EPERM]
The caller does not have appropriate permission to set the required scheduling parameters or scheduling policy.

The *pthread_create*() function may fail if:

[EINVAL]
The attributes specified by *attr* are invalid.

The *pthread_create*() function shall not return an error code of [EINTR].


EXCEPTIONS
EXCEPTIONS EVERYWHERE
makeameme.org

- Exceptions can make your code clean
- Exceptions can make your code fast
- Exceptions can make your code expensive
- $500 million for a crashed Ariane5 rocket in 1996
  - *"The internal SRI software exception was caused during execution of a data conversion from 64-bit floating point to 16-bit signed integer value."*

`http://sunnyday.mit.edu/nasa-class/Ariane5-report.html`

Image source: `https://www.viva64.com/en/b/0426/`

- Issue: Exceptions can be hard to comprehend
  - Which statement can throw which exception?

```
try
{
  MyClass* a = new MyClass();              // std::bad_alloc exception
  MyClass& b = dynamic_cast<MyClass&>(c); // std::bad_cast exception
}
catch (std::exception& e)
{
  std::cout << "Exception: " << e.what() << std::endl;
}
```

- Exceptions do not save you from thinking through all possibilities

- Only use exceptions for error cases
- Specify which exceptions your function throws
  - This must include exceptions your function does not catch
- Catch exceptions at the correct location
  - `main` is likely the wrong location
- Watch out for information leakage if your webserver publicly dumps the exception trace ;)

- Idea: use `goto` as a C-replacement for exceptions
  - Write cleanup error code only once
- Use `goto` for nothing else
  - Only jump forward, not backward

```
char* resourceA = NULL;
FILE* resourceB = NULL;
void* resourceC = MAP_FAILED;
int err = SUCCESS;

resourceA = malloc(10);
if (NULL == resourceA) {
    err = ERROR_A; goto failed;
}
resourceB = fopen(...);
if (NULL == resourceB) {
    err = ERROR_B; goto failed;
}
resourceC = mmap(...);
if (MAP_FAILED == resourceC) {
    err = ERROR_C; goto failed;
}
return SUCCESS;
```

```
failed:
    if (MAP_FAILED != resourceC)
        {
        munmap(resourceC);
    }
    if (NULL != resourceB) {
        fclose(resourceB);
    }
    free(resourceA);
    return err;
```


- Important characteristics
  - Performance
  - Security/safety
  - Features
  - Maintainability
  - Support / community
  - Portability
  - ...


- C, C++
  - High control, high performance
  - Inherently unsafe in many aspects
  - Important use cases
    - C: Low-level kernel/embedded development
    - C++: High-performance application development
    - Maintenance of legacy code
    - Education
- Rust
  - High performance
  - Memory safety and type safety by design
  - Main competitor of C
- App / Web development: look out for other languages ...

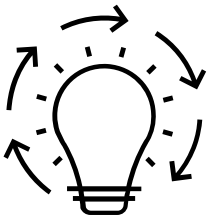
- Idea: By improving code quality we
  - Make code more comprehensible to us and to outsiders
  - Decrease likelihood of introducing bugs
  - Increase likelihood of finding bugs
  - Make code maintainable
  - Make code reusable

- Use descriptive and consistent naming scheme,
  e.g. `local_var`, `myFunc`, `_internalFunc`, `MACRO`, `CONSTANT`
- Wrap if/else/for bodies into { ... }
- Check/sanitize function parameters and return values
- Compare to constant first, e.g. `if (1 == result)`

```
int readPassword(const char* path_password) {
    if (NULL == path_password) {
        return ERROR;
    }
    FILE* file_password = fopen(path_password, "r");
    if (NULL != file_password) {
        return ERROR;
    }
    ...
```

- Use C macros with special care
  - Wrap multiple statements in `do { ... } while(0)`
  - Wrap overall macro expression and each argument in `(...)`
  - Copy macro parameters if used multiple times. It might be a statement with side effects e.g., `i++`
  - If macro has control-flow statements (`return`, `break`, `goto`), include them in the macro name

```
#define CHECK_RETURN_ON_ERROR(stmt, err_msg) do { \
  int result = (int)(stmt); \
  if (result < 0) { \
      printf("CHECK failed with %d: %s", result, err_msg); \
      return result; \
  } \
}
```



- "Do not rewrite your own $THING", especially
  - Parsers
  - Sanitizers
  - Crypto libraries
- Reuse **established** libraries
  - Stackoverflow is not a good source code repository!

PENTEST .BLOG

ADVISORIES OPERATING SYSTEM APPLICATION SECURITY NETWORK TOOLS

# One ring to rule them all – Same RCE on multiple Trend Micro products

October 8, 2017 Mehmet Ince Research

## One ~~ring~~ bug to rule them all – Widgets of Trend Micro's Products

Most of the Trend Micro's products have a widgets for administrator web page. Although core system written with Java/.NET, this widget mechanism had implemented with PHP. That means, they somehow need to put PHP interpreter on product whenever they decided to use widgets. Which makes it a perfect spot to what we need: a single code base, exist across the different product and awesome way to implement reliable exploit once we have an vulnerability.

For the reasons that I've mentioned above, I performed a code audit for widget system of **Trend Micro OfficeScan** product. Result is quite interesting as well as unfortunate for me. I've found 6 different vulnerability but only 2 of them is **0day**.

[…]

## Conclusion

First of all, I would like to say again, this command injection vulnerability has been patched by Trend Micro for both of these products. If you are a Trend Micro user or your organisation is using any of these products, hurry up! Patch your system.

Having same code base on different products is not something bad. I just wanted to point out that one bug within your framework can cause a massive trouble.

# Assume that your code will be reused anywhere

- E.g., Ariane 5 reused code from old rocket without checking its assumptions

- Idea 1: write fully portable code
- Make no assumptions about undefined or implementation-defined behavior
  - Signed overflows
  - Binary shift operation with a negative shift value
  - Return value of {m,c,re}alloc if size is zero (implementation-defined)
- Know undefined behavior of your programming language

  `https://wiki.sei.cmu.edu/confluence/display/c/CC.+Undefined+Behavior`

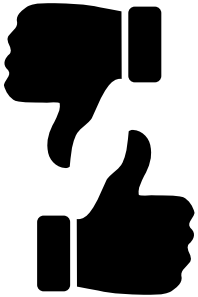
  See no. 51, 52, 53...

- Not all code is fully portable
- Hidden assumptions are dangerous, e.g., `sizeof(int)`
- Idea 2: make all hidden assumptions explicit
- Document them in the comments
- Document them in the code using static asserts and `#ifdef...#error`
  - Both make the compiler fail, thus prevent misuse
  - ☹ Old C does not support static asserts → hacky macros

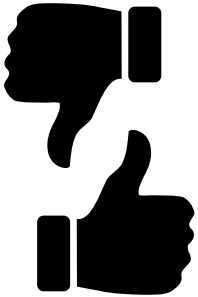
    `http://www.pixelbeat.org/programming/gcc/static_assert.html`
  - ☺ Finally, C11 has native support for static asserts

```
_Static_assert(sizeof(int) == 4, "int must be 4 bytes");
```


- Write documentation
  - Functional behavior
  - Assumptions about input parameters (e.g. overlapping buffers in `memcpy`/`memmove`)
  - Assumptions about architecture, stdlib version, etc.
  - Error behavior
  - Globally visible side-effects (global and static variables)
  - Multithreading safety



- Testing covered in other courses
- When to use asserts and when not?
- 💡 Idea: Asserts reflect invariants of a program
  - In a correct program the invariants would always be satisfied
  - A violation triggers an immediate program abort
- 👉 Asserts are good for testing
- 👉 Asserts are typically turned off for release build
  - No performance penalty
  - `-DNDEBUG` compiler flag
  - ✋ Do not rely on asserts for security!



```c
#define TYPE_A   0
#define TYPE_B   1
#define TYPE_MAX 2

typedef struct {
    unsigned int type;
    size_t pos;
    int data[100];
} struct_t;

void print(struct_t* s)
  assert(s->type < TYPE_MAX); // type must always be valid
  size_t s_len =  sizeof(s->data) / sizeof(s->data[0]);
  assert(s->pos < s_len);   // pos must always be smaller than len
  for (size_t i = 0; i < s->pos; i++) {
      printf("Data: %d\n", s->data[i]);
  }
}
```

# Improve Code Quality: Compiler Support I

- Compile with `-Wall -Wextra -pedantic` and fix all warnings
- Turn warnings into errors `-Werror`
- Use compiler builtins properly, e.g. for integer overflow detection
  `https://gcc.gnu.org/onlinedocs/gcc/Integer-Overflow-Builtins.html`
- Use compiler's runtime sanitizers (`-fsanitize`)
- Use static code analyzers `cppcheck` and `scanbuild`

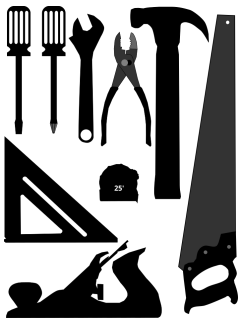
Fortify

- `-D_FORTIFY_SOURCE=2`
- Compiler adds extra checks to detect buffer overflows
- Compiler internally replaces calls to regular string functions with known-length string functions
- Not always possible

# Improve Code Quality: More Resources

- CERT C Programming Language Secure Coding Standard
  - Exhaustive list of typical C-vulnerabilities
  - Memory, arrays, strings, integers, floating point, preprocessor, environment, I/O...
  - Rules, recommendations and example code
  - `https://wiki.sei.cmu.edu/confluence/display/c/SEI+CERT+C+Coding+Standard`
- OWASP Top 10 Web Application Security Risks
  - `https://owasp.org/www-project-top-ten/`

# Summary & Outlook



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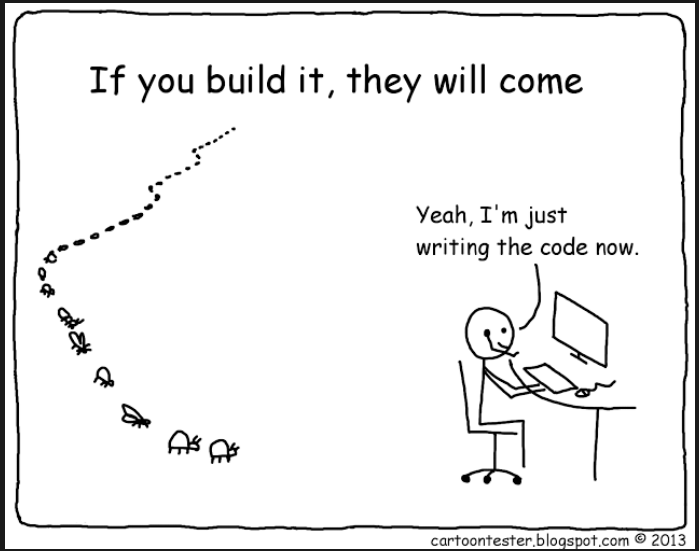
If you build it, they will come
Yeah, I'm just writing the code now.
cartoontester.blogspot.com © 2013