STAC
Apogee Research

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Categories of Current Limitations of Tools (1/2)

- Category 1: The analysis is focused on establishing the limiting (Big O) behavior, disregarding the coefficients of the asymptotic behavior
- Category 2: Tools disregard the lower orders of the order expansion of resource consumption
- Category 3: Tools only consider the bounding behaviors
  - Best case low-consumption path
  - Worst case high-consumption path
- Category 4: Tools focus exclusively on loops
  - There are other ways to amplify vulnerabilities
- Category 5: Tools disregard attacker input budgets
  - Budget may allow for shifting looping behavior to the user side
- Category 6: Tools disregard side effects on the path from user request to response
- Category 7: Tools focus on localized behavior
  - The cause of a vulnerability may be separated from its effect
- Category 8: Tools disregard the combined effect of multiple dimensions of input
- Category 9: Tools don’t model floating point computations

Categories of Current Limitations of Tools (2/2)

- Category 10: In-scope implementation of packet queueing
- Category 11: Tools don’t recognize when constraints can be decoupled prior to reasoning over potential information leakage
- Category 12: Tools assume side channel vulnerabilities require conditional statements
- Category 13: Tools that sample to estimate the complexity curve may miss a high frequency vulnerability with insufficient sampling
- Category 14: Potential SC vulnerabilities can be non-locally balanced
- Category 15: Vulnerability in callback from external library
- Category 16: SC vulnerabilities can leak secret in different domain
- Category 17: Example application with probabilistic complexity function
- Category 18: Extension of category 6; side channel present only in side effects

Cat 1: Coefficients are Disregarded

- Vulnerabilities may go undetected if only analyzing limiting behavior

```
if(guess <= secret)
    for(int i=0; i<n; i++)
        for(int t=0; t<n; t++)
            Consume 1
else
    for(int i=0; i<n; i++)
        for(int t=0; t<n; t++)
            Consume 2
```

- Behavior for guess <= secret is $O(n^2)$
- Behavior for guess > secret is $O(n^2)$
- May conclude program is not vulnerable since complexity is the same for both paths
- However, program is potentially vulnerable since difference in coefficients introduce a differential consumption – in this case itself of order $O(n^2)$

Cat 2: Lower Orders are Disregarded

- Vulnerabilities may go undetected if only analyzing the highest complexity code section

```
for(int i=0; i<n; i++)
    Consume 1000 ms              // SECTION A
    for(int t=0; t<n; t++)
        Consume 1 ms             // SECTION B
```

- Input budget (AC): n <= 99,
  Resource consumption: < 60 s

- Max resource consumption of highest complexity: $1*99^2$ = **9.801 s (< max)**
- Max total resource consumption: $1*99^2 + 1000*99$ = **108.801 s (> max)**

- If only considering only highest complexity, program may be deemed not vulnerable
- However, program exceeds budget after accounting for the lower orders

Cat 3: Only Best & Worst Case Bounds Considered (1/3)

```
if(guess <= Secret){
    if(T == 1){Thread.sleep(1);}
    else if(T == 2){
        for(int i = 0; i < n; i++){Thread.sleep(1);}
    else{
        for(int i = 0; i < n*n*n; i++){Thread.sleep(1);}
}
else{
    if(T == 1){Thread.sleep(1);}
    else if(T == 2){
        for(int i = 0; i < n*n; i++){Thread.sleep(1);}
    else{
        for(int i = 0; i < n*n*n; i++){Thread.sleep(1);}
}
```

Cat 3: Only Best & Worst Case Bounds Considered (2/3)

```
if(guess <= Secret){
    if(T == 1){Thread.sleep(1);}
    else if(T == 2){
        for(int i = 0; i < n; i++){Thread.sleep(1);}
    else{
        for(int i = 0; i < n*n*n; i++){Thread.sleep(1);}
}
else{
    if(T == 1){Thread.sleep(1);}
    else if(T == 2){
        for(int i = 0; i < n*n; i++){Thread.sleep(1);}
    else{
        for(int i = 0; i < n*n*n; i++){Thread.sleep(1);}
}
```

SC Time vulnerability

Cat 3: Only Best & Worst Case Bounds Considered (3/3)

- Side Channels may go undetected if ruled out exclusively through Best and Worst Case comparison of alternative paths

```
if guess <= Secret
    if T == 1        Consume 0
    else if T == 2   Consume N
    else             Consume N^3
else
    if T == 1        Consume 0
    else if T == 2   Consume N^2
    else             Consume N^3
```

- Regardless of the guess and Secret, the best case resource consumption is 0
- Regardless of the guess and Secret, the worst case resource consumption is N^3
- This may lead some tools to conclude there is no differential resource consumption and therefore no side channel
- However, a case with differential resource consumption (N vs N^2) is hiding between the best and worst case paths

Cat 4: Only Loops are Considered (1/3)

```
boolean verifyCreds(String pwd){
    int index = -1;
    for(char x : pwd) {
        if(!correct(x, idx++)){return false;}
        delay();
    }
    return true;
}
…
if verifyCreds(pwd)
    Privileged Action 1
…
if verifyCreds(pwd)
    Privileged Action 2
…
if verifyCreds(pwd)
    Privileged Action N
…
```

Cat 4: Only Loops are Considered (2/3)

```
boolean verifyCreds(String pwd){
    int index = -1;
    for(char x : pwd) {
        if(!correct(x, idx++)){return false;}
        delay();
    }
    return true;
}
…
if verifyCreds(pwd)
    Privileged Action 1
…
if verifyCreds(pwd)
    Privileged Action 2
…
if verifyCreds(pwd)
    Privileged Action N
…
```

Weak SC Time vulnerability

Cat 4: Only Loops are Considered (3/3)

- Vulnerabilities may go undetected if focusing only on loops and their effects, disregarding other ways to amplify the effect of the fundamental cause of a vulnerability (loop or otherwise)

Weak CAUSE of SC (in this case a loop)

```
bool verifyCreds(String pwd)
    int idx = -1
    for(char x: pwd)
        if !correct(x, idx++)
            return false
        else
            delay()
    return true
```

Amplified Effect

```
if verifyCreds(pwd)
    Privileged Action 1
…
if verifyCreds(pwd)
    Privileged Action 2
…
if verifyCreds(pwd)
    Privileged Action N
…
```

- The differential resource consumption of verifyCreds() is too weak to leak secret
- However, when invoked multiple times, the differential consumption is amplified

Cat 5: Input Budgets are Disregarded

- Vulnerabilities may go undetected because tools only analyze individual interactions
- Looping may be shifted to input side by applying budget for multiple (cheap) interactions rather than a single (expensive) interaction; e.g. sampling a weak SC multiple times, or aggregating resource consumption

```
while(true)
    listen for connection
    lookup session state based upon cookie
    if no state found allocate session (Expensive)
    handle requests of session
    end connection and eventually timeout state
```

- There may be no way to exhaust the resources through normal conops of establishing a session and then spending the input budget on exchanging requests and responses
- However, an attacker may apply the input budget towards establishing many back to back sessions, in total exceeding the resource threshold
- Asymmetric cost to application compared to attacker

Cat 6: Side Effects are not Considered

- Vulnerabilities may go undetected if focusing only on the input to output relationships

```
bool verifyCreds(String input)
    bool correct_length = correctLength(input)
    bool can_print = true
    for(char c: input)
        if !correct(c) && can_print
            send "Error" packet
            can_print = false
        delay()
    return can_print && correct_length
```

- Constant consumption from Input to Output regardless of position of first wrong character
- However, timing of output "Error" packet allows segmented guessing

Cat 7: Focus is Limited to Localized Behavior

- Vulnerabilities may go undetected if the cause and effect of a vulnerability are separated

```
public class Foo
    private int[] m

    // Constructor
    public foo(int[] n)
        m = new int[n.size * n.size]

    // Some Method
    public void Bar()
        for(int i: m)
            Consume 1
```

- Complexity of Bar() is O(m.size), but this means O(n.size^2)!

Cat 8: Only Consider a Single Dimension of Input

- Vulnerabilities may go undetected if effect of multiple dimensions of user input is disregarded

```
f1(int n, int m, int p)
    for(int i=0; i<n; i++)
        f2(m,p)

f2(int m, int p)
    for(int i=0; i<m; i++)
        f3(p)

f3(int p)
    for(int i=0; i<p; i++)
        Consume 1
```

- Complexity of $O(n*m*p)$ may be just as bad as $O(n^3)$

Cat 9: Tools Don't Model Floating Point Math (1/2)

```
private static void function(int x){
    double N = 10000000005.0;
    double z = 0;
    for(int i = 0; i<x; i++){ // z = N*x
        z+=N;
    }
    double w = z/x; // w = z/x = N*x/x = N
    if((long)Math.abs(N - w) != 0){
        // Do computationally expensive calculation
        // Shouldn't happen since w == N
        Thread.sleep(30000);
    }
}
```

Cat 9: Tools Don't Model Floating Point Math (2/2)

- Vulnerabilities due to floating point computation errors may not be caught if the tool does not include a model of floating point computations

```
double w = z/x; // w = z/x = N*x/x = N
if((long)Math.abs(N - w) != 0){
    // Do computationally expensive calculation
    // Shouldn't happen since w == N
    Thread.sleep(30000);
}
```

- Resource Consumption of function depends on the integer component of the absolute value of the floating point error of the addition and division operations.
- Resource Consumption:
  - 30,000 : 6,755,396 < x < 7,355,882 (Approximately 6% of the valid user inputs)
  - 0 : 0 < x < 6,755,397 and 7,355,881 < x < 10,000,000

Cat 10: In-scope implementation of packet queuing vulnerability

- Packet queuing vulnerability counts as in-scope if a mechanism for maintaining the request queue is contained within application.
- Max response time n seconds, queue size q
  - Vulnerable: resource usage limit $\leq n * q$.
  - Non-vulnerable: resource usage limit $> n * q$

Cat 11: Tools Don't Recognize De-coupled Constraints

- Some constraints can be decoupled into sets of constraints which can be analyzed independent of one another.

```
void process(g,s){
  if(g ≤ s){Δ}
  else{~0}}
```

Case A

```
process(g,s)
if(t_0)
  if(t_1)
    …
      if(t_n)
      else{}
    …
  else{}
else{}
```

Case B

```
if(t_0)
  if(t_1)
    …
      if(t_n)
          process(g,s)
      else{process(g,s)}
    …
  else{process(g,s)}
else{process(g,s)}
```

- Cases A and B are equivalent, the set of variables $\{g, s\}$ and the set of variables $\{t_1, t_2, t_3, \dots, t_n\}$ can be analyzed independently.
- The decoupling is more obvious in case A than in case B

Cat 12: Tools Assume SCs Require Conditional Statements (1/3)

- Side channel vulnerabilities can occur without conditional branches. Exception handling for example can be use to cause a side channel vulnerability. The JVM treats conditionals and exceptions differently. The following authentication algorithm uses conditionals to define branching conditions.

```
seqCorrect = exceedLen = 0
bool verifyCreds(String input)
    for(int x =0;x<input.length();x++)
        checkChar(candidate,x+1)
    return seqCorrect == input.length() && exceedLen == 0

void checkChar(String input, int i)
    if(i >= password.length()){exceedLen++}
    else if(password.charAt(i-1) == input.charAt(i-1)){
        if(seqCorrect+1 == i){
            seqCorrect++
            delay()
        }
    }
```

Delay incurred only if all previous chars and current char are correct

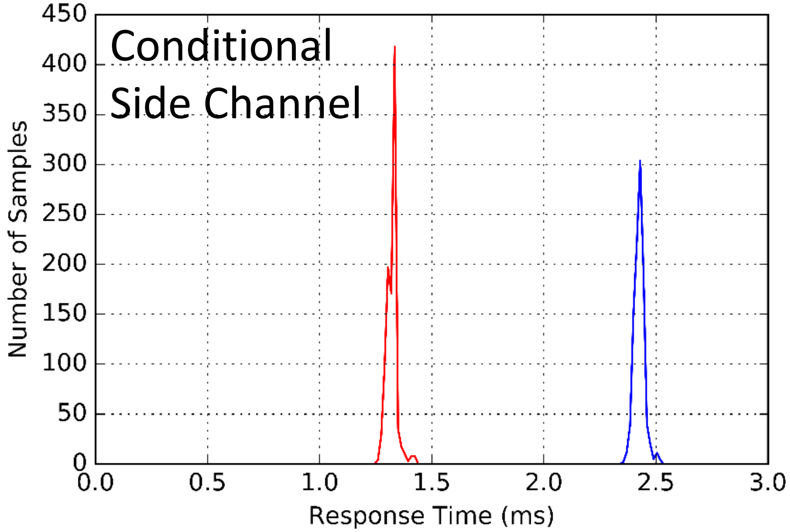
Cat 12: Tools Assume SCs Require Conditional Statements (2/3)

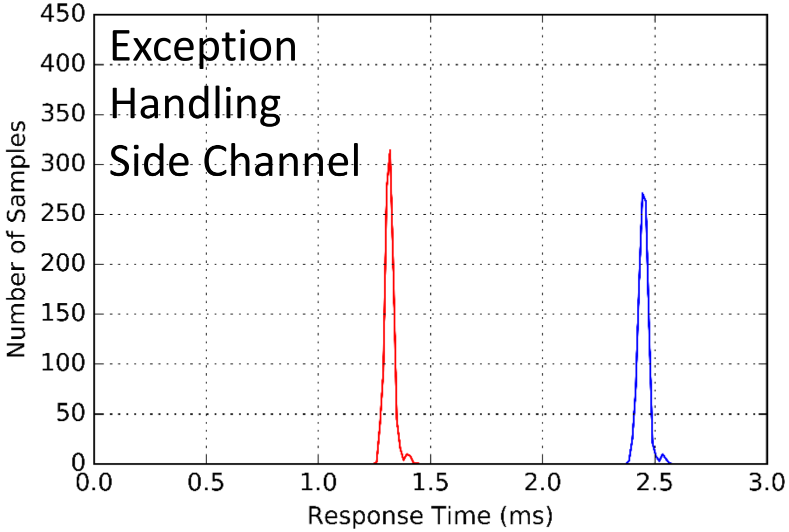
- The authentication algorithm's checkChar method can be re-written with exception handling in place of conditionals.

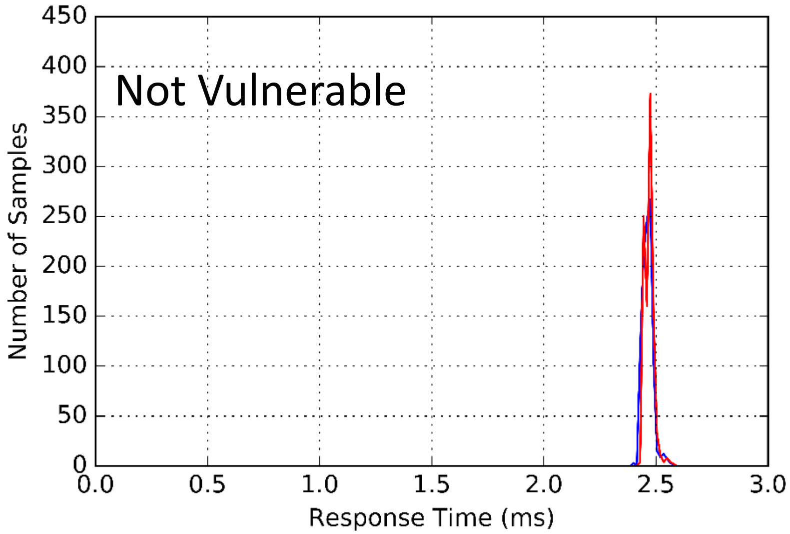
```
void checkChar(String input, int i)
    try{equal=100/(password.charAt(i-1)-input.charAt(i-1))
    }catch(ArithmeticException e1){checkSeqCorrect(i)
    }catch(StringIndexOutofBoundsException e3){
        exceedLen++}

void checkSeqCorrect(int i)
    try{equal=100/(seqCorrect+1 - i)
    }catch(ArithmeticException e2){
        seqCorrect++
        delay()}
```

Delay incurred only if all previous chars and current char are correct

Cat 12: Tools Assume SCs Require Conditional Statements (3/3)





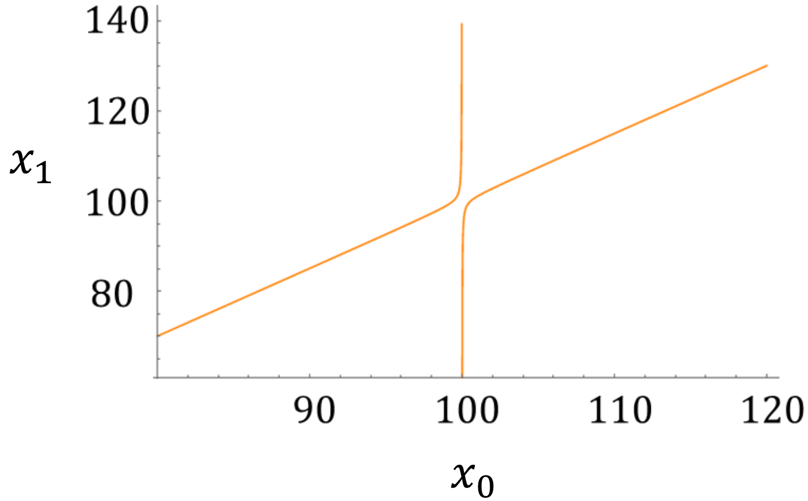


Char 1 Incorrect	
Char 1 Correct	

Cat 13: Sampling Complexity (1/3)

- Tools that under-sample the input range to estimate the complexity function of an application may miss a high frequency spike in the complexity curve.
- Category 13 application uses Newton's method to calculate the roots of a function.
- Newton's method: $x_{n+1} = x_n + \frac{f(x_n)}{f\prime(x_n)}; f(x) = (x - M)^2 - \varepsilon$
  - Roots are: $M \pm \sqrt{\varepsilon}$
  - Terminating condition: $|x_{n+1} - x_n| < d$ and $f(x_n) < d$
  - As $x_0 \rightarrow M$ or $x_0 \rightarrow \infty$, $x_1 \rightarrow \infty$. As $x_1 \rightarrow \infty$, the number of steps to reach the terminating condition approaches infinity.
- 2 vulnerable regions around $x_0 = 100$
- Input budget allows for value positive values up to $10^{3000} - 1$
- Percentage of vulnerable x_0 values:

$$\frac{2 * 10^{531}}{3 * 10^{3003}} = 6.67 * 10^{-2471}\%$$



Cat 13: Sampling Complexity (2/3)

$M = 100; \varepsilon = 1; d = 10^{-100}$

BigDecimal $f(x)$ {return $(x - M)^2 - \varepsilon$}

BigDecimal $d(x)$ {return $2(x - M)$}

BigDecimal nextX(x)

    return $x - \frac{f(x)}{d(x)}$

int newtonMethod(x_0)

    n = 0

    xCurrent = x_0

    do{

        x_P = x_C

        x_C = nextX(x_P)

        n++

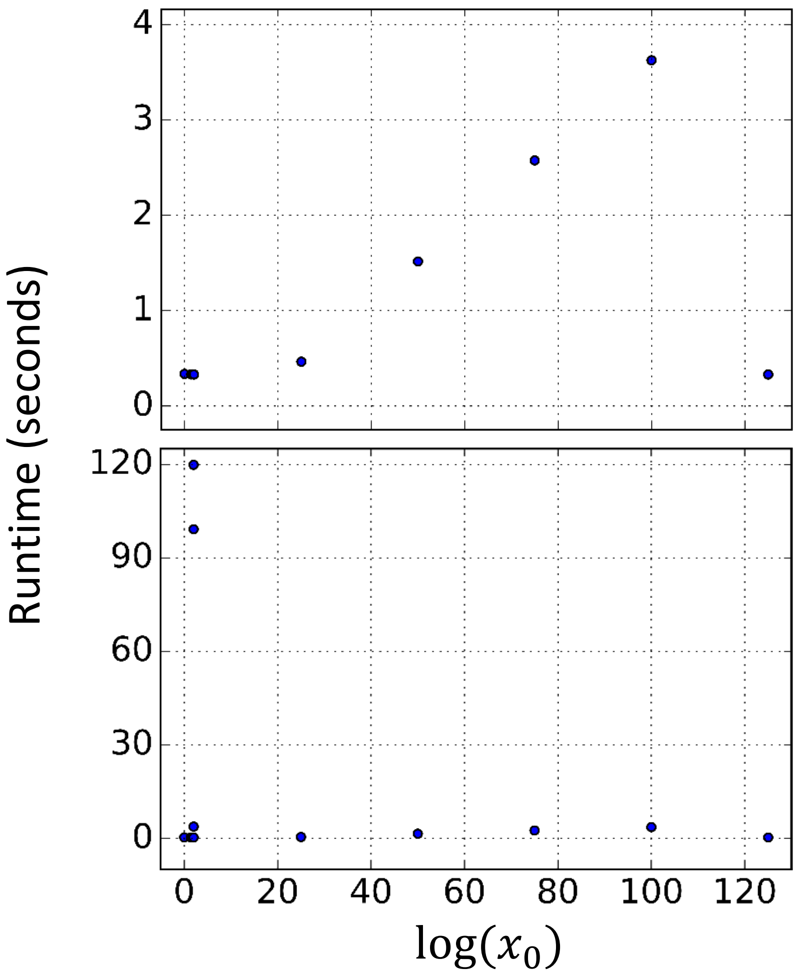
    }while($|x_C - x_P| < d$ and $f(x_C) < d$)

    return n

Cat 13: Sampling Complexity (3/3)

- AC Time experimental data using E5+ AC Time definition:
  - Benign user input: $x_0 = 0$; normal runtime: 0.34 seconds

x_0	Runtime (seconds)
0	0.34
50	0.33
99.9	0.33
$100 - 10^{-100}$	3.80
$100 - 10^{-2465}$	99.21
$100 - 10^{-2996}$	119.87
101	0.33
10^{50}	1.52
10^{75}	2.58
10^{100}	3.62
10^{125}	0.33



Cat 14: Non-local balancing for SC (1/3)

- Tools that perform SC analysis on individual methods or code structures may misclassify an application as vulnerable in cases where for example a timing imbalance in one region of the code is offset in another region of the code leaving the application non-vulnerable as a whole.

```
seqCorrect = exceedLen = 0
void checkChar(String input, int i)
    if(i >= password.length()){exceedLen++}
    else if(password.charAt(i-1) == input.charAt(i-1)){
        if(seqCorrect+1 == i){
            seqCorrect++
            delay()
        }
    }

bool verifyCreds(String input)
    for(int x =0;x<input.length();x++)
        checkChar(candidate,x+1)
    balance(input.length() - seqCorrect)
    return seqCorrect == input.length() && exceedLen == 0
```

Delay incurred only if all previous chars and current char are correct

Delay incurred for each sequentially correct character

Cat 14: Non-local balancing for SC (2/3)

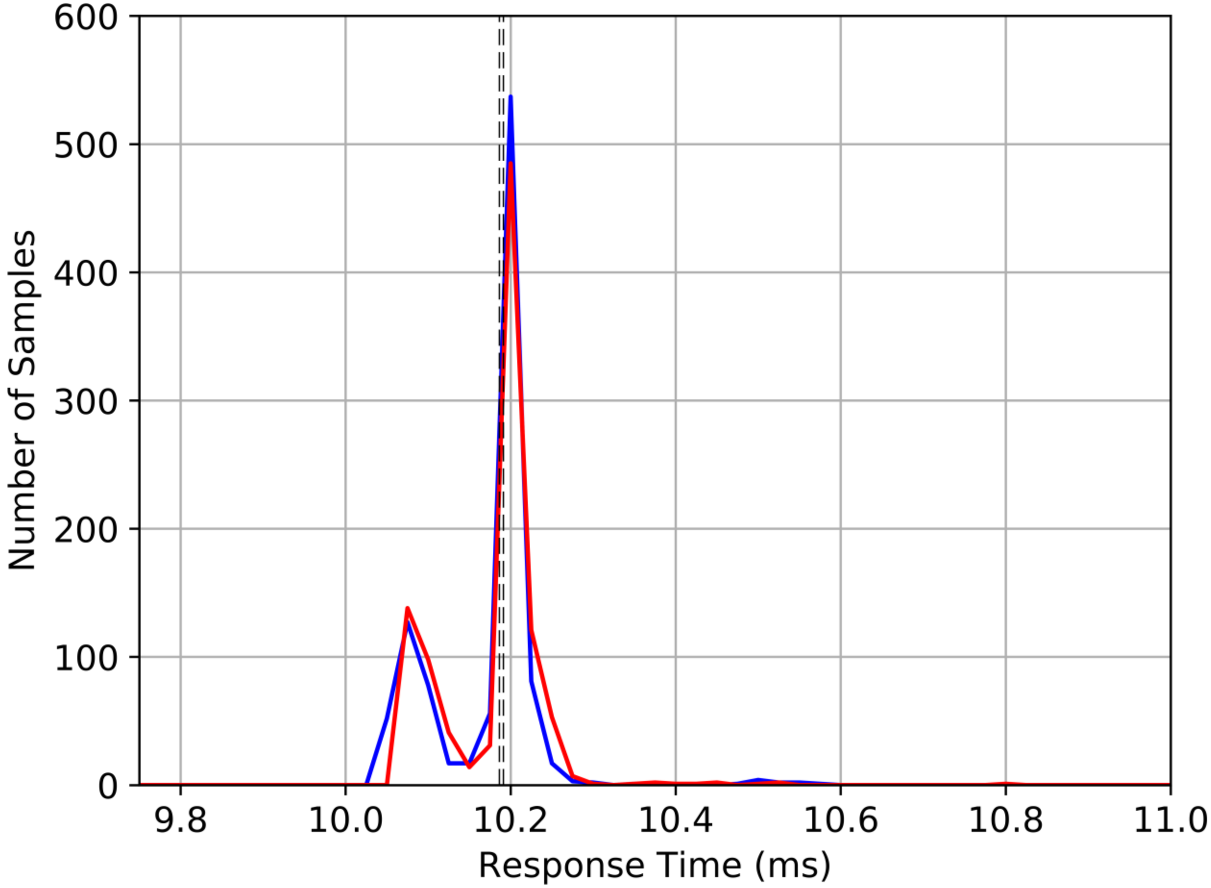
```
void balance(int offset)
    for(int x =0;x<offset;x++)
        delay()
```

Delay incurred for each incorrect character after the first incorrect character is reached

```
seqCorrect = exceedLen = 0
bool verifyCreds(String input)
    for(int x =0;x<input.length();x++)
        checkChar(candidate,x+1)
    balance(input.length() - seqCorrect)
    return seqCorrect == input.length() && exceedLen == 0
```

Delay incurred for each user-provided character preventing a side channel

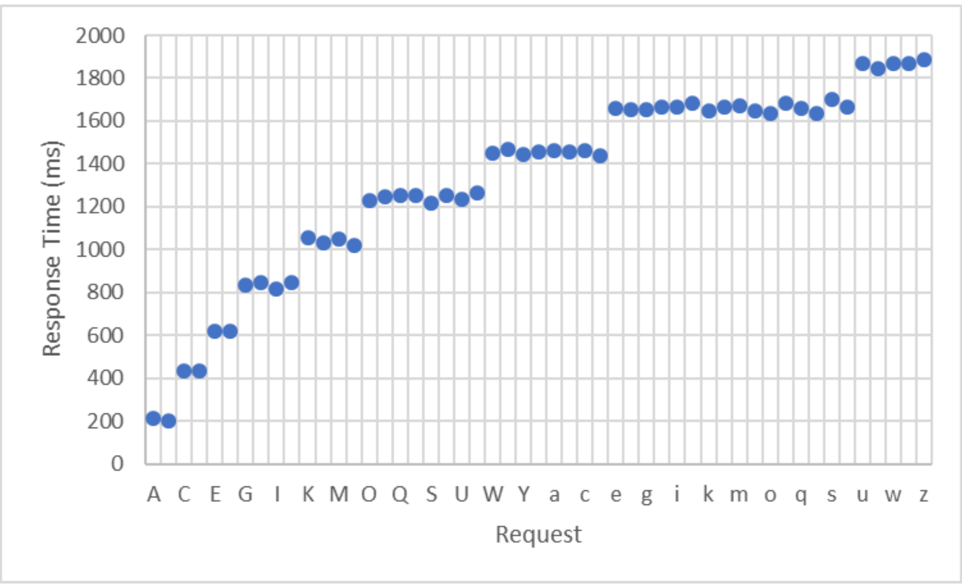
Cat 14: Non-local balancing for SC (3/3)



Char 1 Incorrect	
Char 1 Correct	

Cat 15: External Library Callback Vulnerability

- Demonstrates a vulnerability in a callback from an external library method
- java.util.TreeSet uses a tree data structure maintain a sorted order of added elements
- All elements must implement java.lang.Comparable interface (the compareTo() method)
- java.util.TreeSet calls the application's compareTo() method to set the element order
- The application implements a compareTo method that when combined with the java.util.TreeSet data structure results in a vulnerability

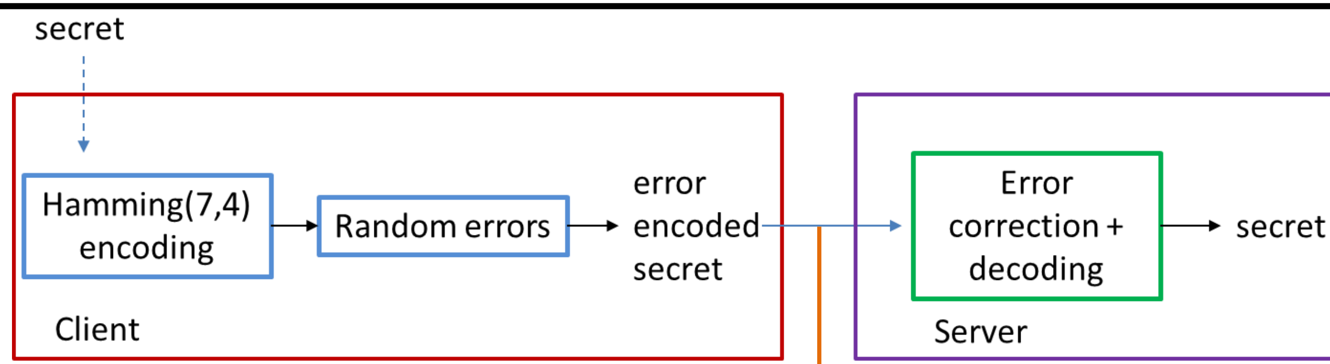


Attacker requests: "A",…,"Z", "a",…, "x"
Benign request: "z"

Cat 16: Leaking secret in a different domain (1/3)

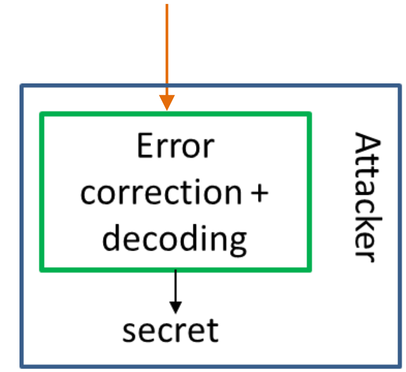
- Applications can leak information on secrets in a transformed domain. Provided a mapping from the transformed state to the secret, leaked information + reverse transformation = secret
- Logically equivalent to an encryption side channel that leaks private keys: encrypted secret + decryption with leaked keys = secret
- Category16 application demonstrates this using a simple-to-analyze Hamming(7,4) linear encoding. Note: Applications can contain more complex non-linear transformations of the secret
  - Client converts secret x to data r and sends r to the server. The server receives r converts it back to the secret x and stores x.
  - The same secret x can result in different values of r
  - Side channel: when the client sends r, bit 0 takes 30 ms and bit 1 takes 60 ms
  - Attacker can determine r from the side channel and use the same algorithm as the server to get the secret x from r.

Cat 16: Leaking secret in a different domain (2/3)




```
prepare(String r){//r as binary string
  for(char bit: r.toCharArray()){
    if(bit == '1'){
      delay(30) //30 ms delay}
    delay(30)
    send(bit)
  }
}
```

$$bit = 0; \Delta_t = 30\ ms$$
$$bit = 1; \Delta_t = 60\ ms$$



Cat 16: Details on hamming encoding (3/3)

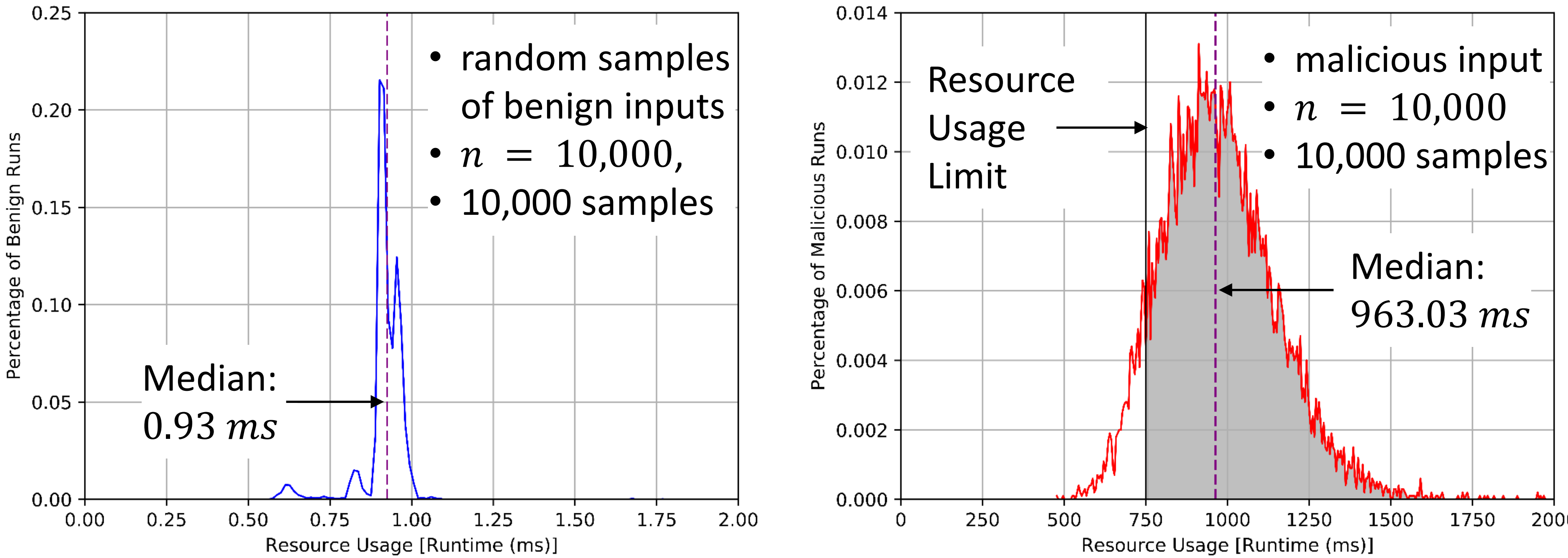
- Hamming (7,4) encodes 4 data bits and detects and corrects cases where a single transmitted bit is accidentally flipped (single bit error).
  - Encodes 4 data bits, p, with 3 parity bits using matrix G
  - Transmitted data: $x = Gp$ (x is the 7 transmitted bits)
  - Matrix H ($HG = [0]$) is used to check errors: $z = Hr$, where r is the 7 received bits
    - if no errors occurred: $r = x$ and $z = Hx = [0]$
    - If single bit error at received bit i: $r = x + e_i$ and $z = Hx + He_i = He_i$
  - If only a single bit error occurs, z indicates which bit is incorrect. That bit is flipped to result in x
  - Matrix R is used to decode x: $Rx = RGp = p$ (4 original data bits)
- Code from server can be used to determine the secret, x, from the data leaked from the side channel, r
  - Entropy of leaked data $>$ entropy of the secret. Leaked data (7 bits), secret (4 bits)
  - Transmitted data (r, Hamming encoding + 1-bit error) may appear to have sufficient entropy resulting in a weak SC
  - The side channel leaks r. Knowledge of operations with G, H, and R creates a deterministic mapping from leaked data r to the secret x.

Cat 17: Probabilistic Complexity Function (1/2)

- Probabilistic algorithms are used to solve problems ranging from primality testing to sorting algorithms.
- For example, Quicksort is a sorting algorithm that continually segments the list of items to be sorted.
  - At each step, a pivot parameter controls how the list of items is partitioned into smaller sub-lists.
- Quicksort ranges in complexity from $\mathrm{O}(n \log n)$ to $\mathrm{O}(n^2)$ (given n items) depending on the pivot selection.
  - In the best case, $O(n \log n)$, partition sizes are approximately equal
  - In the worst case, $O(n^2)$, the pivot is always the largest or smallest item; given a sub-list of size m, partition sizes are 0, and $m - 1$
- A probabilistic Quicksort implementation with random pivot selection provides a mean performance of $\mathrm{O}(n \log n)$ for any given input.
- This vulnerable probabilistic Quicksort implementation randomly selects the pivot position, but heavily favors selecting the n^{th} item in the list of n items.

Cat 17: Probabilistic Complexity Function (2/2)

- An attacker can use this knowledge to provide a sorted list of the maximum allowed size ($n = 10{,}000$). A benign user request will be delayed by the time to process this malicious request.



- Input Budget: 100 kB
- Resource Usage Limit: 750 ms
- Probability of Success: 50%

Cat 18: Extension of Cat 6; Side Effect-Only SC (1/3)

- Category 6 demonstrates a case where side effects can introduce side channels. This extension demonstrates a case where a strong side channel exists only in timings between side effects.

```
verifyCredentials(String guess, PrintWriter out) {
    int correct = 1;
    noise(); // 𝒩(μ = 200 ms, σ = 50 ms)
    out.println("STATUS: Start Check");
    for (int x = 0; x < guess.length(); x++) {
        delay(1); //1 ms
        if (guess.charAt(x) == password.charAt(x)) {
            correct *= 1;
        }
        else {
            if (correct == 1) {out.println("STATUS: Bad Char");}
            correct *= 0;
        }
    }
    noise(); // 𝒩(μ = 200ms, σ = 50ms)
    return correct==1 && guess.length()==password.length();
```

Cat 18: Extension of Cat 6; Side Effect-Only SC (2/3)

```
verifyCredentials(String guess, PrintWriter out) {
    …
    out.println("STATUS: Start Check");
    …
    out.println("STATUS: Bad Char");}
    …
return correct==1 && guess.length()==password.length();
```

- Secret: password; lowercase alphabet; worst-case 10 characters
- Probability of correctly determining the first character in 26 operations by selecting the character with maximal response time:
  - Strong SC (Side Effect to Side Effect) – 99.99%
  - Weak SC (Start to Side Effect) – 3.97%
  - Weak SC (Side Effect to End) – 3.97%
  - Weak SC (Start to End) – 3.92%
  - Guessing – 3.85%
- Side Channel Strength: 260 operations, 99% probability of success

Cat 18: Extension of Cat 6; Side Effect-Only SC (3/3)