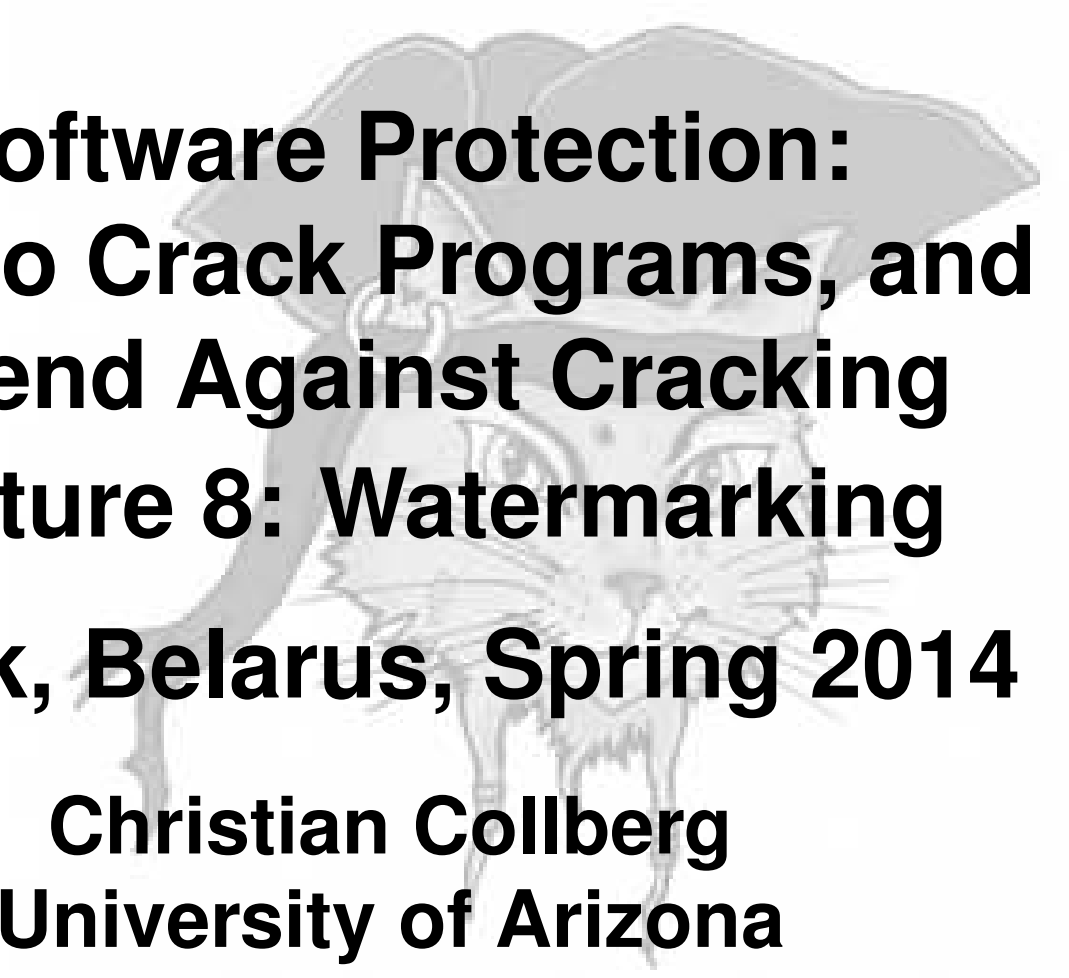

Software Protection: How to Crack Programs, and Defend Against Cracking

Lecture 8: Watermarking

Minsk, Belarus, Spring 2014

Christian Collberg
University of Arizona

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Today's lecture

1. Watermarking

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- Embed a unique identifier into the executable of a program.

.

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- A watermark is much like a *copyright notice*.

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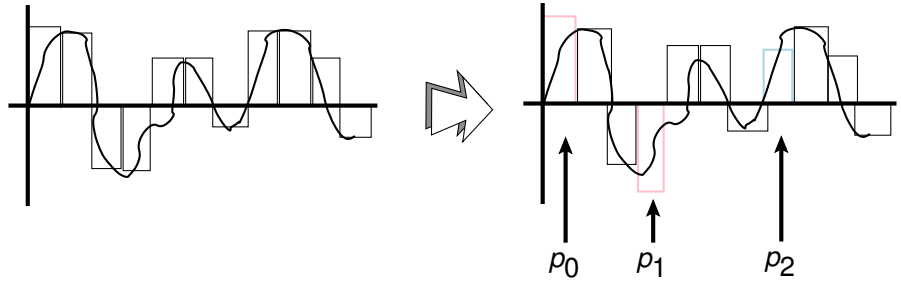
- Allows us to show that the program the attacker claims to be his, is actually ours.
- *Software fingerprinting*: every copy you sell will have a different unique mark in it
- Trace the copy back to the original owner, and take legal action.

History and Applications

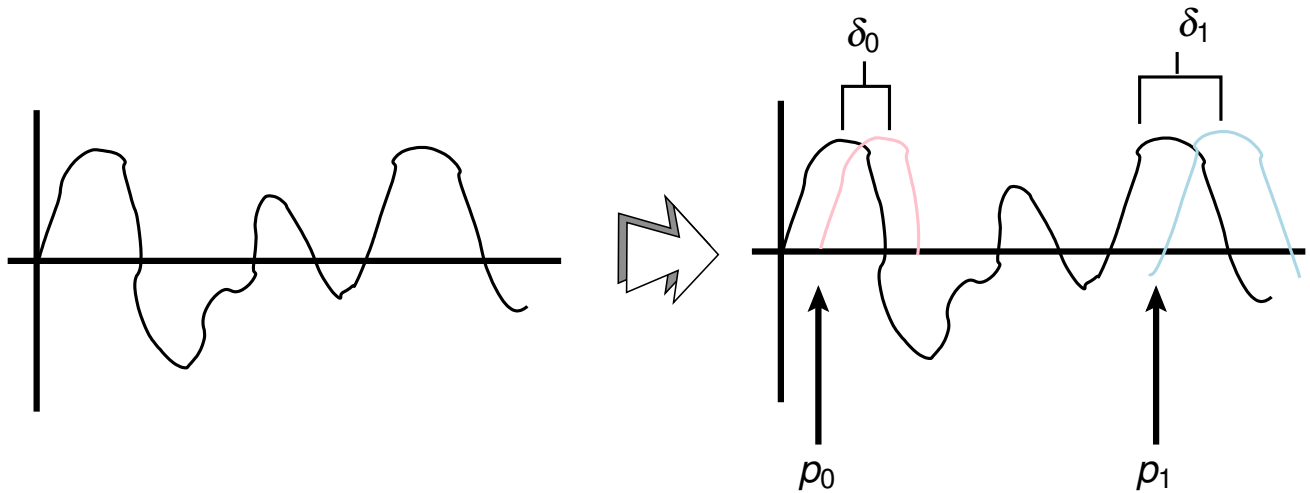
p. 468




Authorship mark
((in)visible,robust)
Fingerprint mark
(invisible,robust)
icensing mark
(invisible,robust)
Customer #27182818
Customer #31415926
© 2006 Collberg
<license object="kitten.jpg">
<grant to="Alice">
<right> copy-once </right>
</grant>
</license>
alidation mark
(visible,fragile)
MD5(kitten.jpg)
0xc6ba8f25d2dfc44cf518d7f327c8e83f
"Cute kitten in window in Venice"
"Attack mice at dawn"
PG-13
Filtering mark
(visible,robust)
Meta data mark
(visible,fragile)
Secret mark
(invisible,fragile)

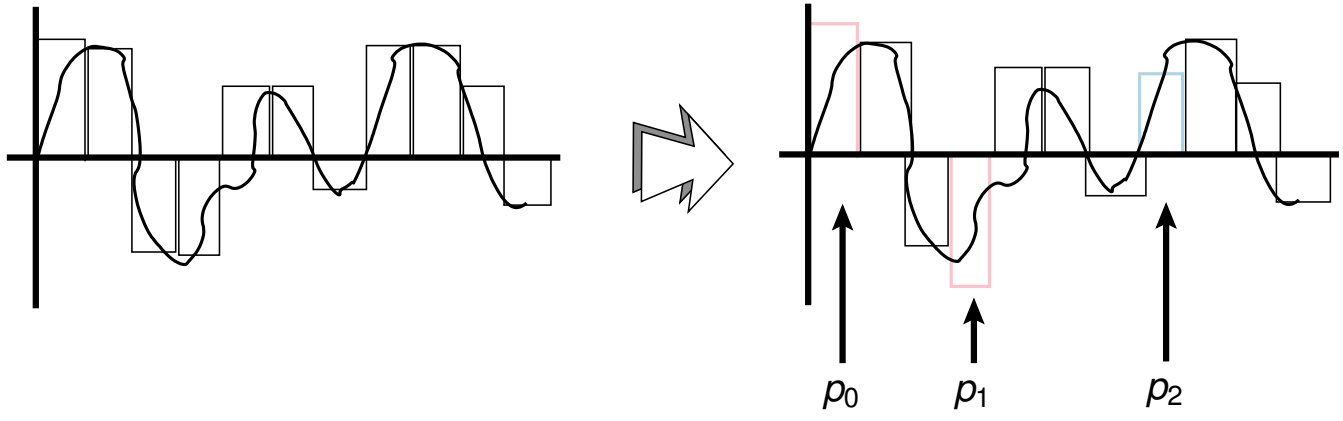
Audio marking: Echo hiding

- Embed echoes that are short enough to be imperceptible to the human ear:



Audio: Least Significant Bit

- LSB of an audio sample is the one that contributes least to your perception,



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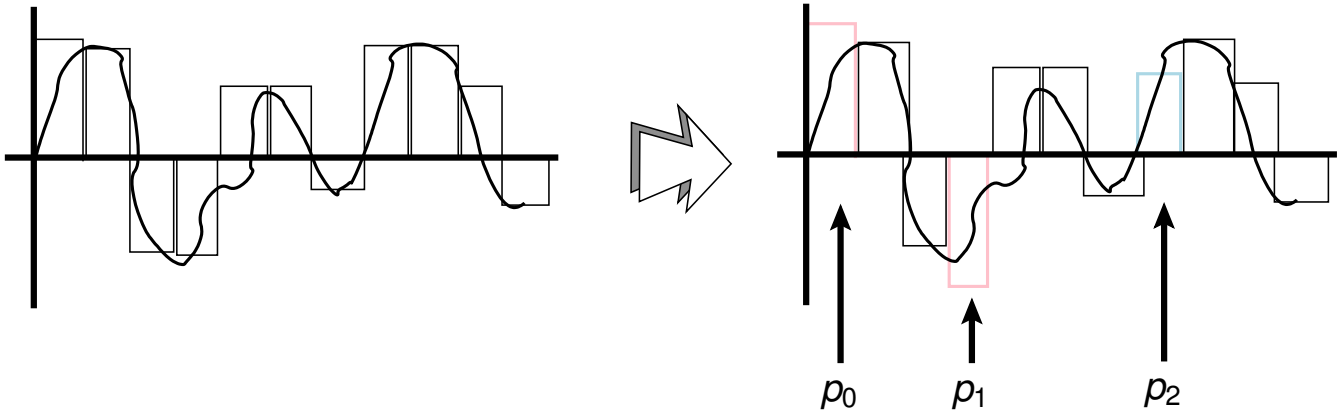


Audio: Least Significant Bit

- LSB of an audio sample is the one that contributes least to your perception,
- Alter without adversely affecting quality!
- *Attack*: randomly replace the least significant bit of every sample!

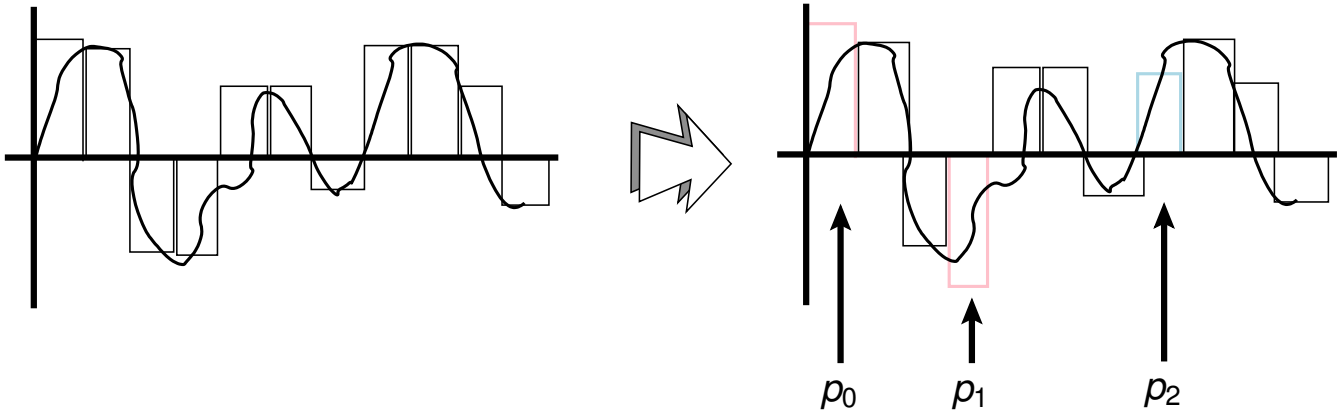
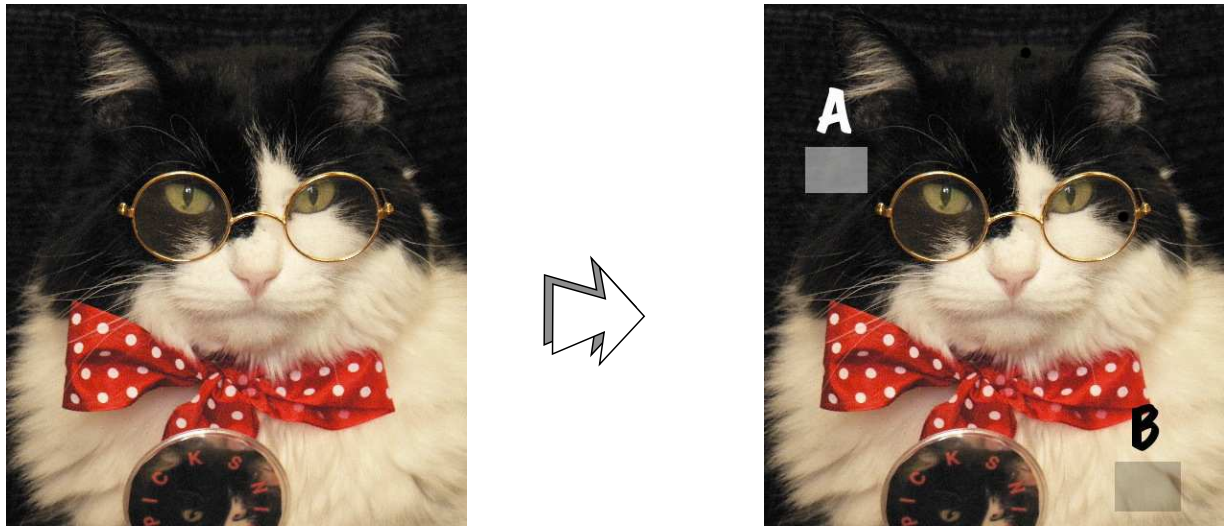


Image: Patchwork

- Embed a single bit by manipulating the brightness of pixels.



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- Embed a single bit by manipulating the brightness of pixels.
- Use a pseudo-random number sequence to trace out pairs (A, B) of pixels

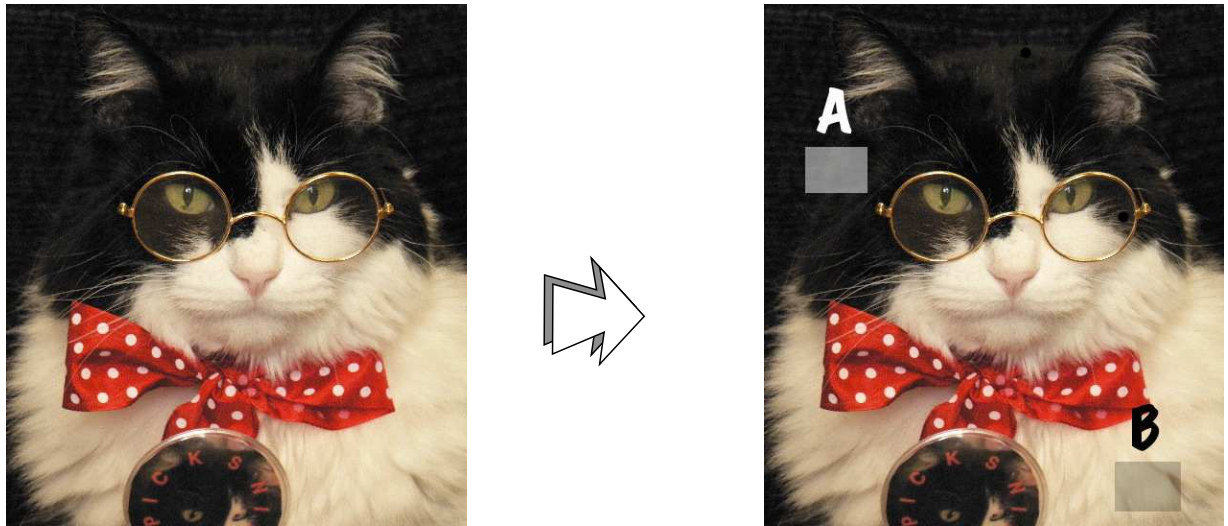
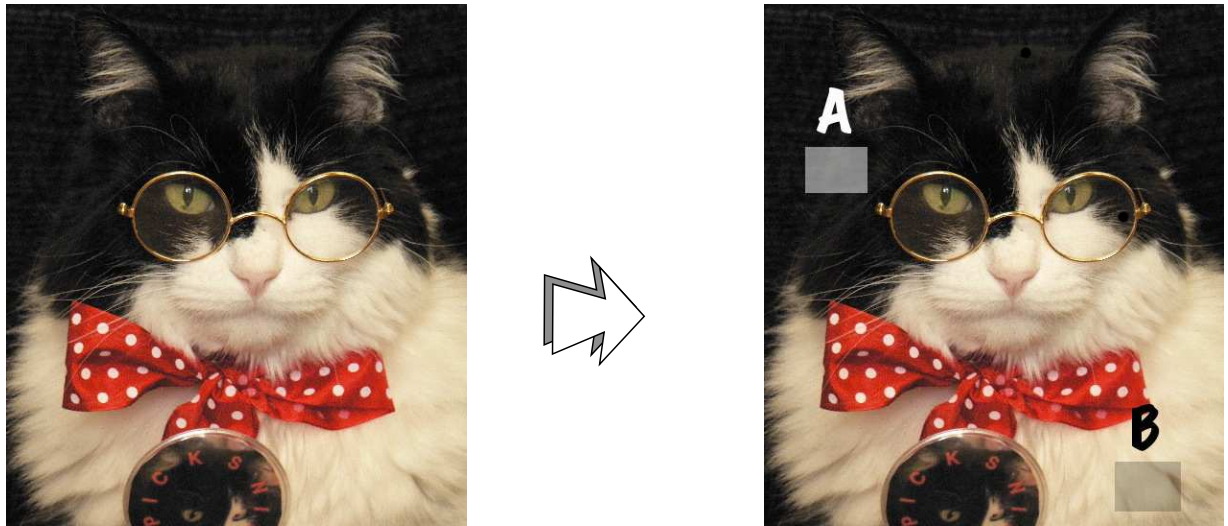


Image: Patchwork

- Embed a single bit by manipulating the brightness of pixels.
- Use a pseudo-random number sequence to trace out pairs (A, B) of pixels
- During embedding adjust the brightness of A up by a small amount, and B down by the same small amount:



Patchwork: Embedding And Recognition

EMBED(P, *key*):

1. `Init_RND(`*key*`);` $\delta \leftarrow 5$
2. $i \leftarrow$ `RND()`; $j \leftarrow$ `RND()`
3. Adjust the brightness of pixels a_i and b_i: $a_i \leftarrow a_i + \delta$; $b_j \leftarrow b_j - \delta$
4. repeat from 2 ≈ 10000 times

□

RECOGNIZE(P, *key*):

1. `Init_RND(`*key*`);` $S \leftarrow$
2. $i \leftarrow$ `RND()`; $j \leftarrow$ `RND()`
3. $S \leftarrow S + (a_i - b_j)$
4. repeat from 2 ≈ 10000 times
5. if $S \gg 0 \Rightarrow 0$ output `"marked!"`

Blind vs. Informed

- Watermarking recognizers are either *blind* or *informed*.

Blind vs. Informed

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- To extract a blind mark you need the marked object and the secret key.

Blind vs. Informed

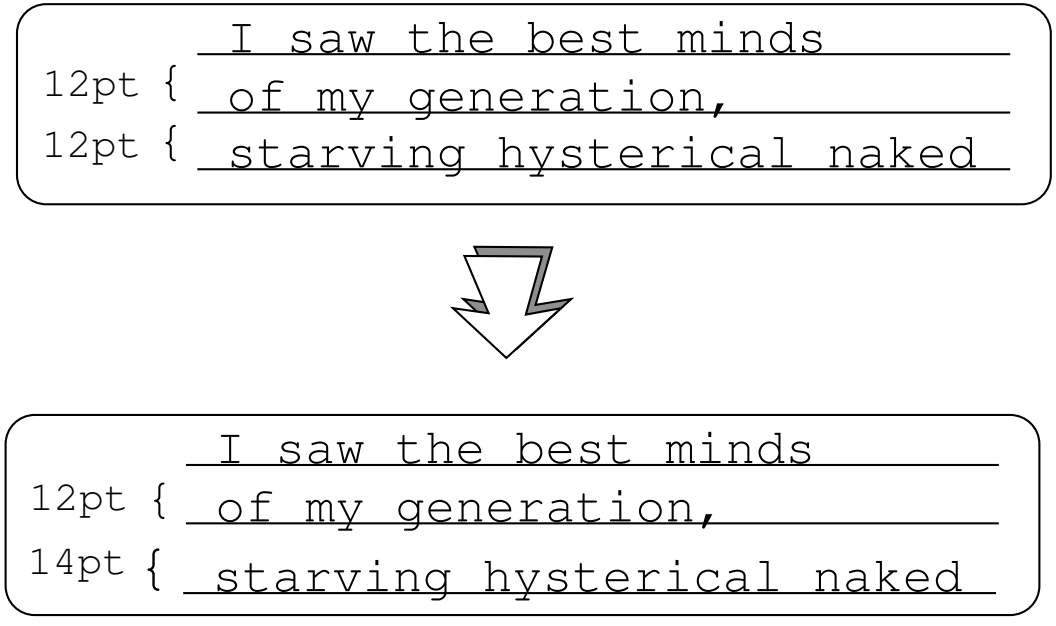
- Watermarking recognizers are either *blind* or *informed*.
- To extract a blind mark you need the marked object and the secret key.
- To extract an informed mark you need extra information, such as original, unwatermarked, object.

Watermarking text

- Cover object types:
  - the text itself with formatting (ASCII text); or
  - free-flowing text;
  - an *image* of the text (PostScript or PDF).

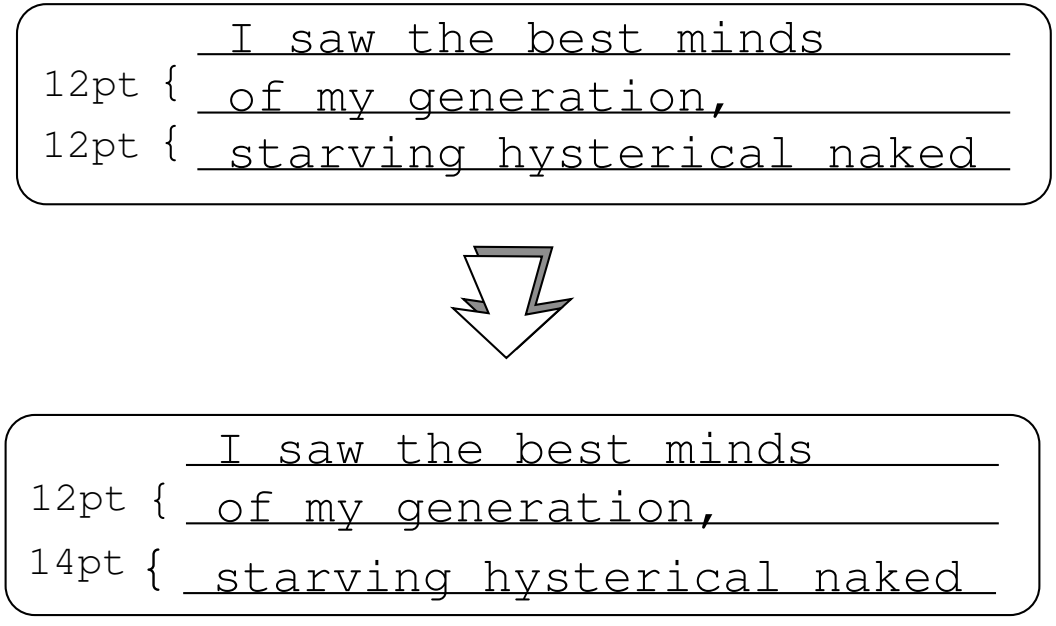
Watermarking Text: PDF

- Similar to marking images.



Watermarking Text: PDF

- Similar to marking images.
- Example: encode 0-bit or a 1-bit by hanging word/line spacing.



Watermarking Text: formatted ASCII

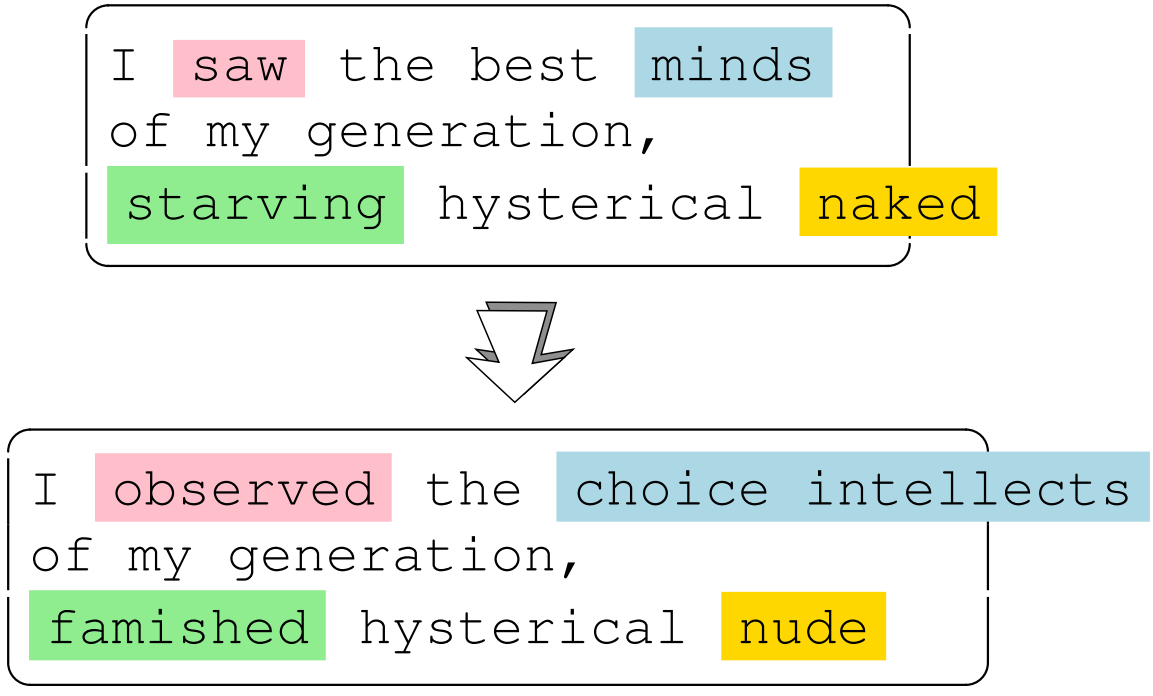
- Encode the mark in white-space: 1 space = 0-bit, 2 spaces = 1-bit:

```
I␣saw␣the␣best␣minds
of␣my␣generation,
starving␣hysterical␣naked
```

```
I␣␣␣saw␣␣the␣best␣␣␣minds
of␣␣␣␣␣␣␣my␣␣␣generation,
starving␣hysterical␣naked
```

Watermarking Text: Synonym replacement

- Replace words with synonyms.
- Insert spelling or punctuation errors.



Watermarking Text: Syntax

- Encode a mark in the syntactic structure of an English text:
  1. Devise an extract function which computes a bit from a sentence,
  2. Modify the sentence until it embeds the *right* bit.

```
I saw the best minds
of my generation,
starving hysterical naked
```

```
It was the best minds
of my generation that I saw,
starving hysterical naked
```

Watermarking Text: Atallah et al.

1. Chunk up the watermark, embed one piece per sentence.
2. A function computes one bit per syntax tree node.
3. Modify sentence until these bits embed a watermark chunk.
4. A *marker* sentence precedes every watermark-bearing sentence.

```
I saw the best minds
of my generation,
starving hysterical naked
```

Watermarking Text: Atallah et al.

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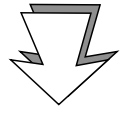
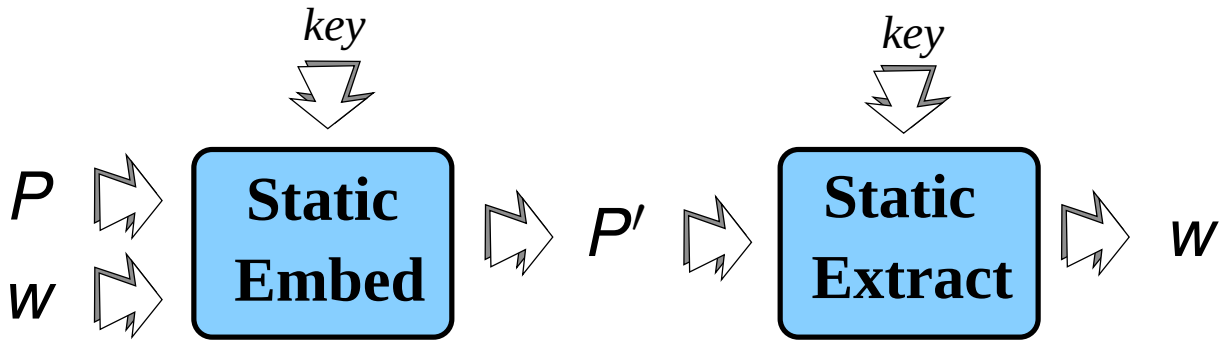


I saw the best minds of my generation. They were starving hysterical naked. None, baby, none were smarter than them. Nor more lacking in supply of essential nutrients or in more need of adequate clothing. Baby.

Watermarking Software

p. 478

Static watermarks



You care about

- Encoding bitrate
- Stealth
- Resilience to attack

Ideas for Software Watermark Algorithms

Encode the watermark

- in a permutation of a language structure

Ideas for Software Watermark Algorithms

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- in an embedded media object

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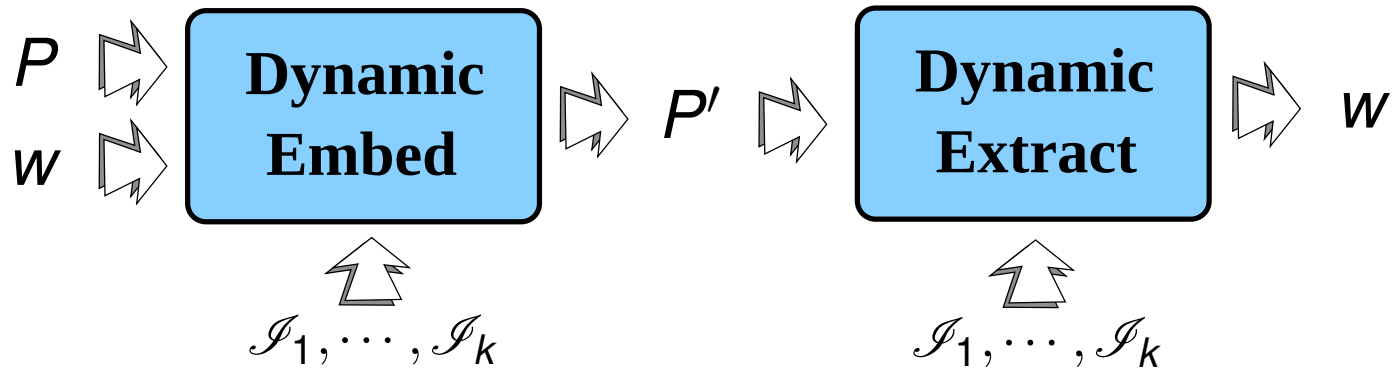
Ideas for Software Watermark Algorithms

Encode the watermark

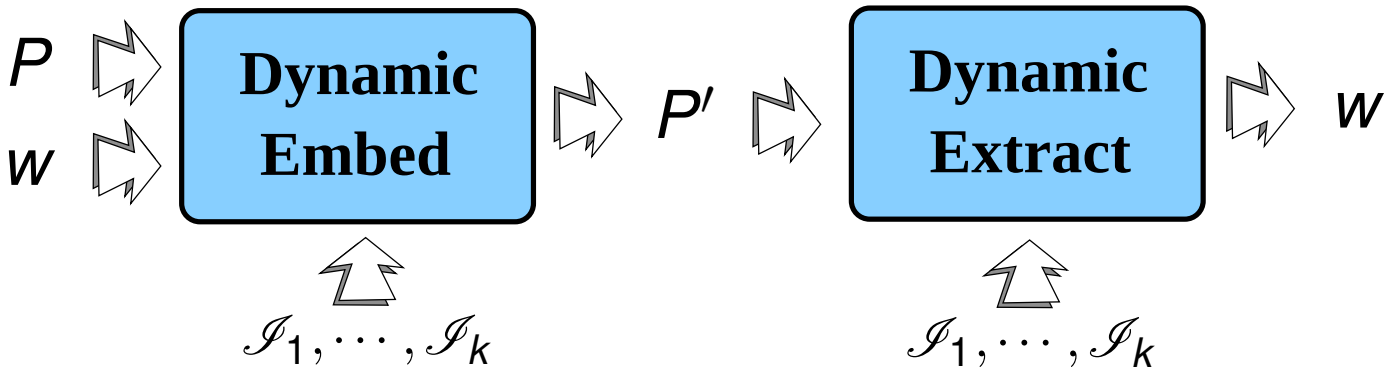
- in a permutation of a language structure
- in an embedded media object
- in a statistical property of the program
- as a solution to a static analysis problem
- in the topology of a CFG

Dynamic watermarks



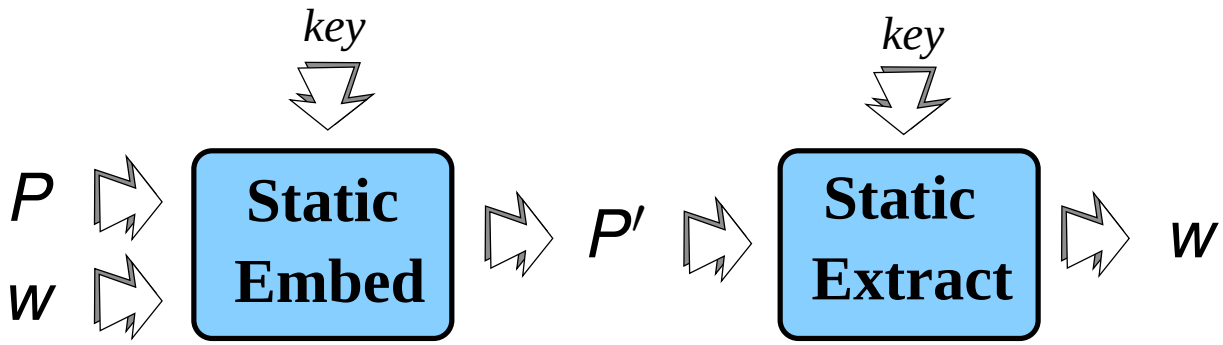
- Encode the watermark in the runtime state of the program

Dynamic watermarks



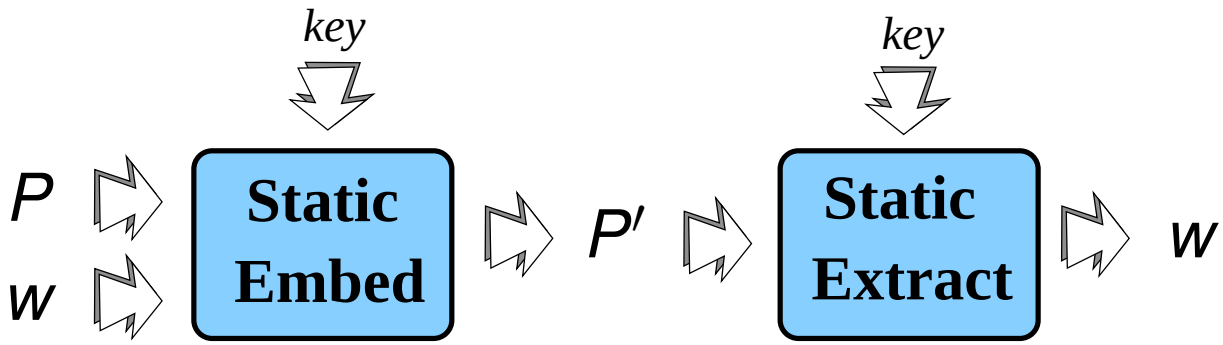
- Encode the watermark in the runtime state of the program
- Dynamic marks appear more robust, but are more cumbersome to use

Attacks against software watermarks



- The adversary knows the algorithm

Attacks against software watermarks



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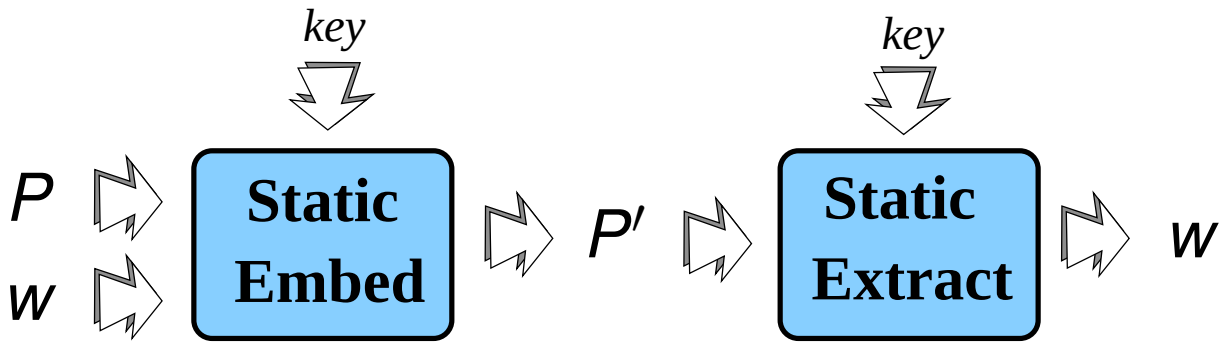

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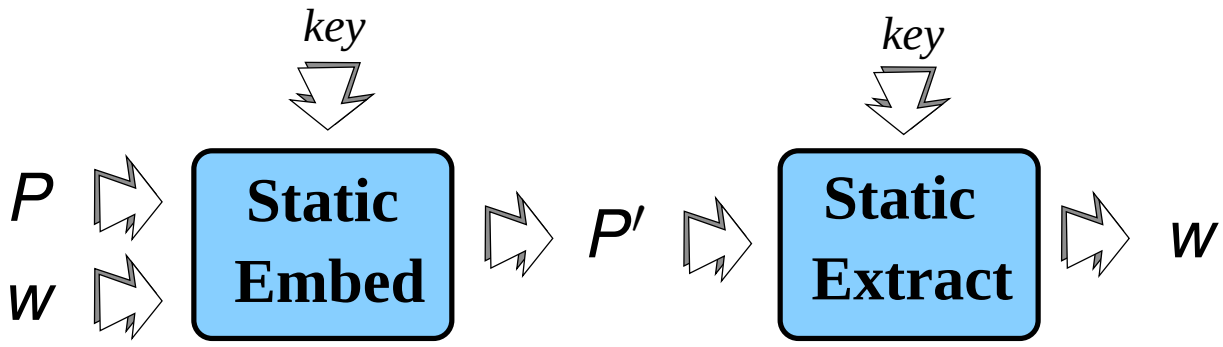

- The adversary knows the algorithm
- The adversary has complete access to the program
- The adversary doesn’t know the key
- The adversary doesn’t know the embedding location (it’s key dependent)

Attacks — Rewrite attack

- Alice has to assume that Bob will try to destroy her marks before trying to resell the program!
- One attack will always succeed. . .

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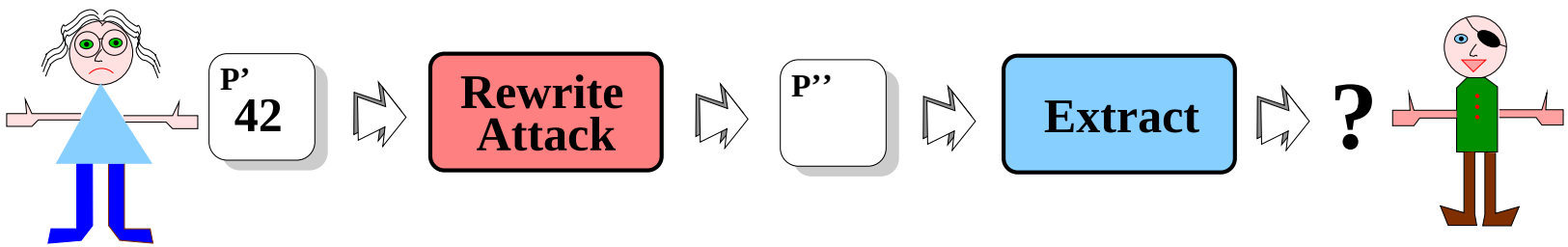
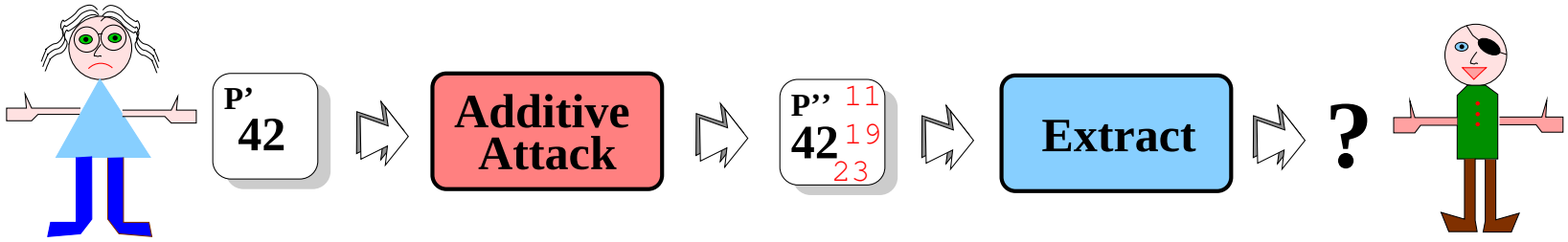


- Ideally, this is the *only* effective attack.

Attacks — Additive attack

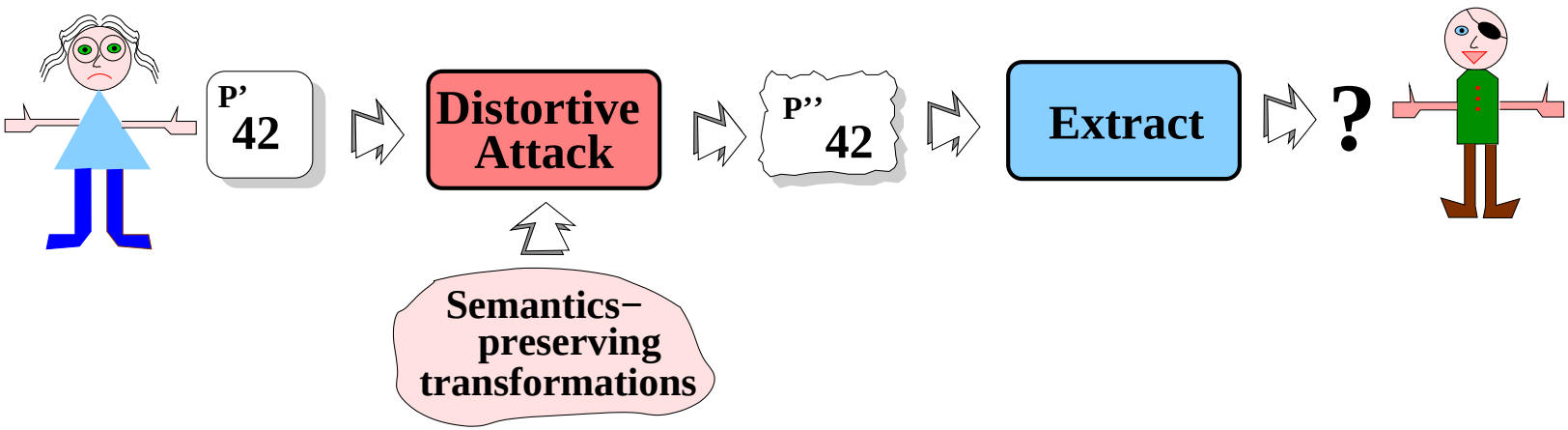
- Bob can also add his own watermarks to the program:



- An additive attack can help Bob to cast doubt in court as to whose watermark is the original one.

Attacks — Distortive attack

- A distortive attack applies semantics-preserving transformations to try to disturb Alice's recognizer:



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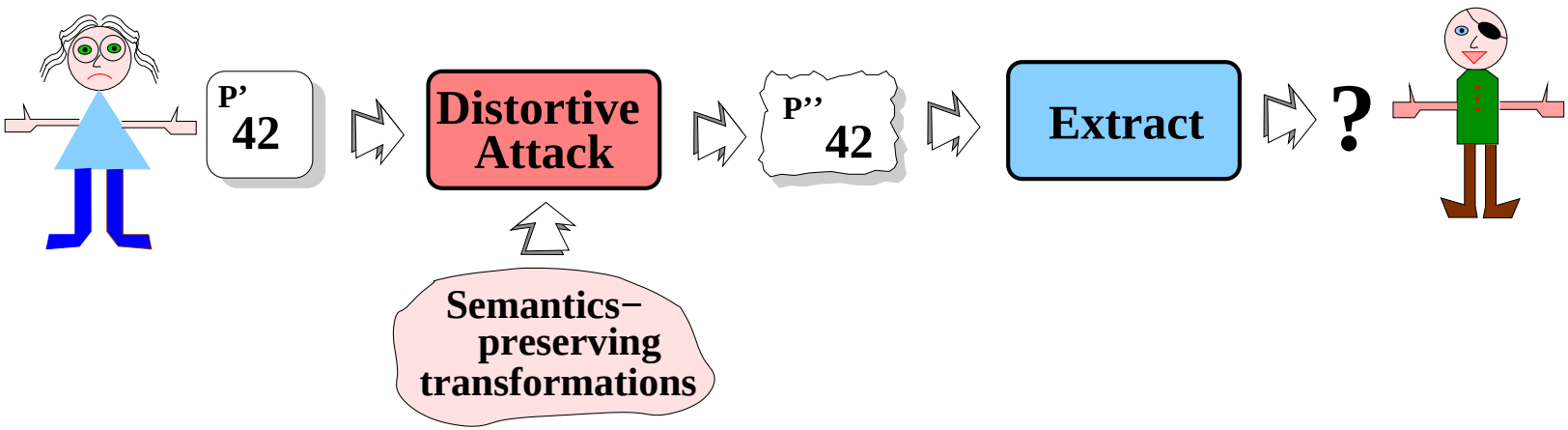
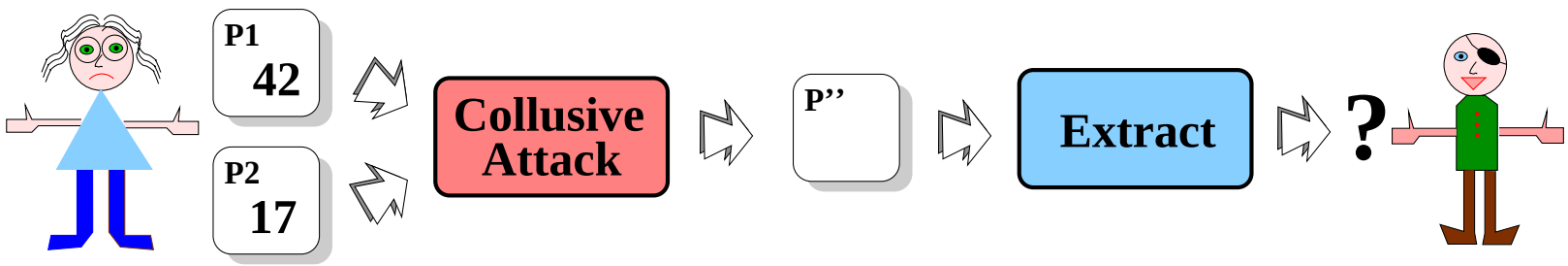


- Transformations: code optimizations, obfuscations,...

Attacks — Collusive attack

- Bob buys two differently marked copies and comparing them to discover the location of the fingerprint:



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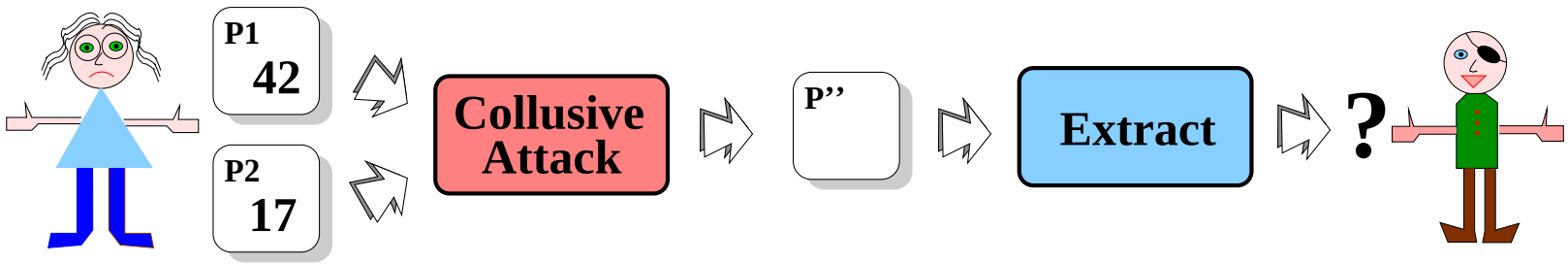
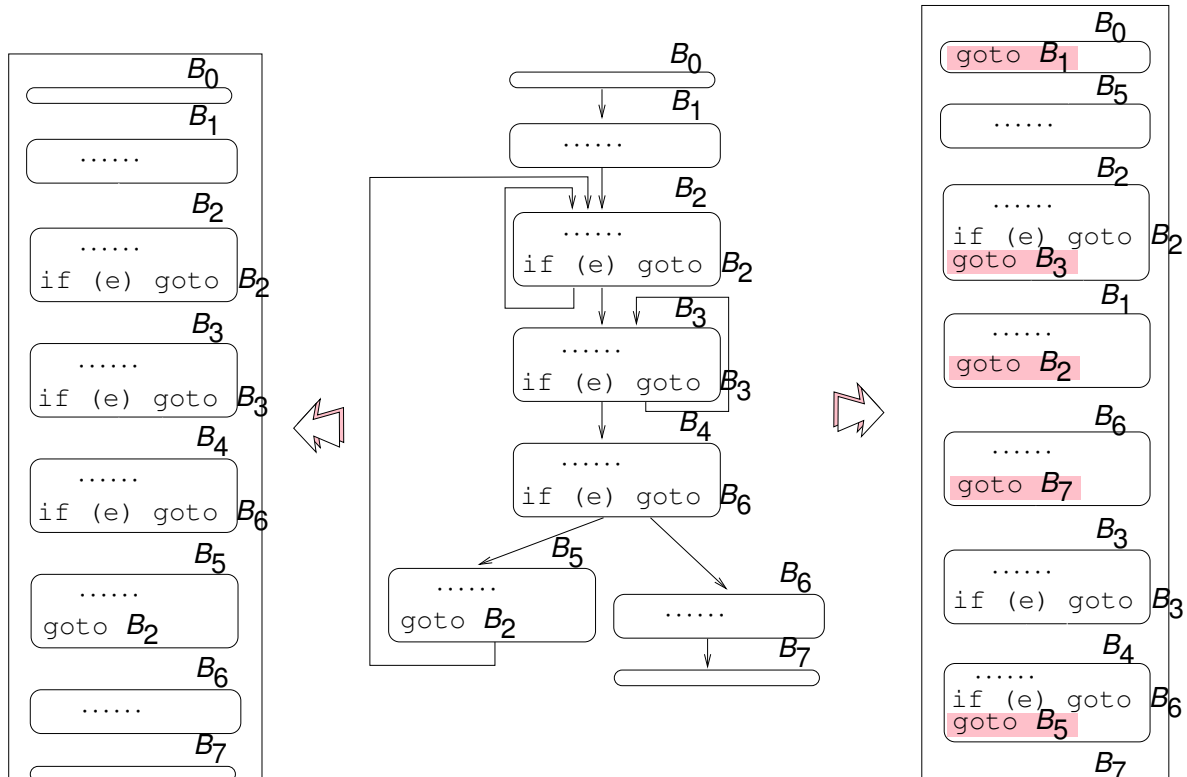


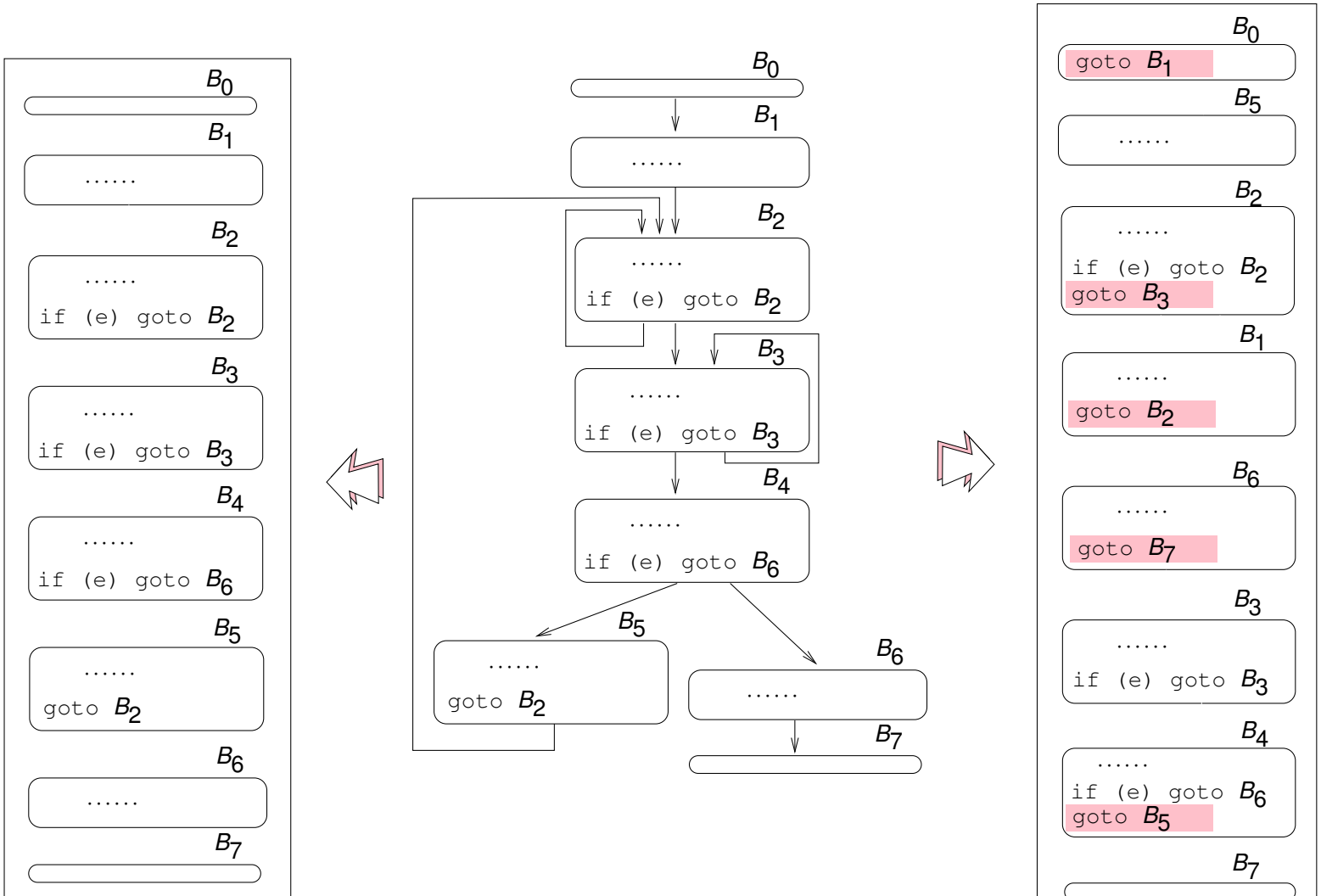
- Alice should apply a different set of obfuscations to each distributed copy, so that comparing two copies of the same program will yield little information.

Watermarking by Permutation

p. 486



Algorithm WMDM: Reordering Basic Blocks



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  $$\log_2(m!) \approx \log_2(\sqrt{2\pi m}(m/e)^m) = \mathcal{O}(m \log m)$$

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  watermarking bits.
- What about stealth?

Tamperproofin Watermarks

p. 494

```
Code decode (Image m) {
   ...
}
Image tudou =
```


```
void main() {
   Code c = decode(tudou);
   int x = c.execute(42)
}
```

Algorithm wmMC: Media watermark

```
int foo (int x) {
   ...
}
```

```
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```

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- Bob uses Stirmark to destroy marks in embedded images!

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Algorithm WMVVS

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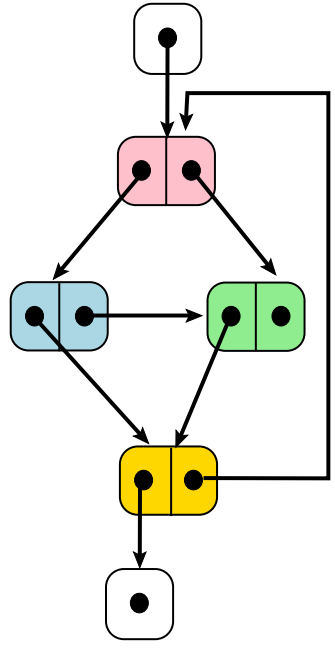
Watermarks in CFGs



Algorithm WMVVS: Watermarks in CFGs

- Basic idea:
  1. Embed the watermark in the CFG of a function.

Algorithm wmVVS: Watermarks in CFGs

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Algorithm WMVVS: Watermarks in CFGs

- Basic idea:
  1. Embed the watermark in the CFG of a function.
  2. Tie the CFG tightly to the rest of the program.
- Issues:
  1. How do you encode a number in a CFG?
  2. How do you find the watermark CFG?
  3. How do you attach the watermark CFG to the rest of the program?

Algorithm wmVVS: Embedding

- Generate a stealthy watermark CFG:
  1. basic blocks have out-degree of one or two

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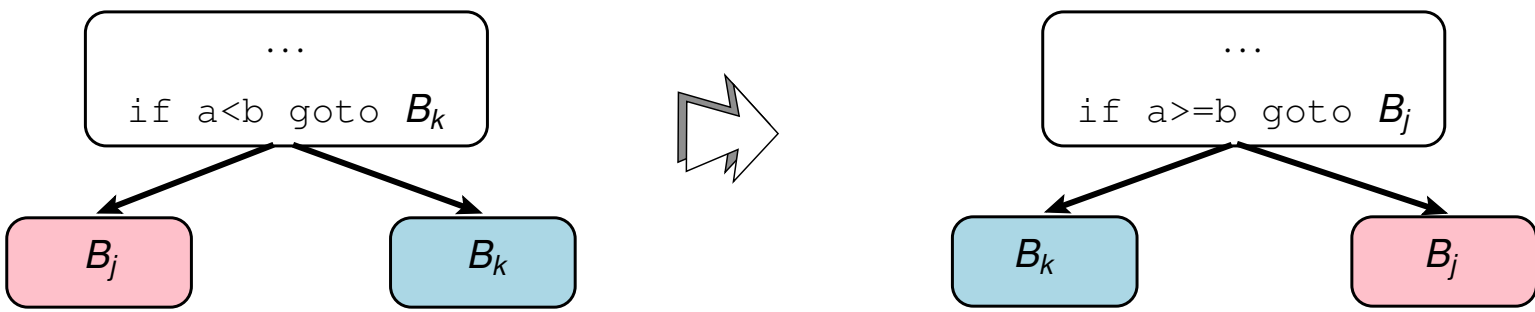
  3. it is shallow (real code isn't deeply nested)
  4. it is small (real functions aren't big)
  5. it is resilient to edge-flips:



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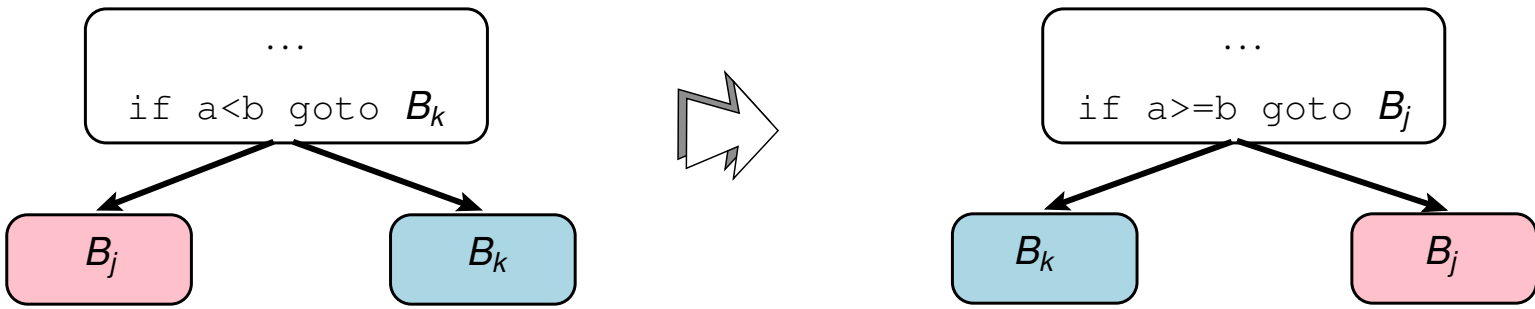
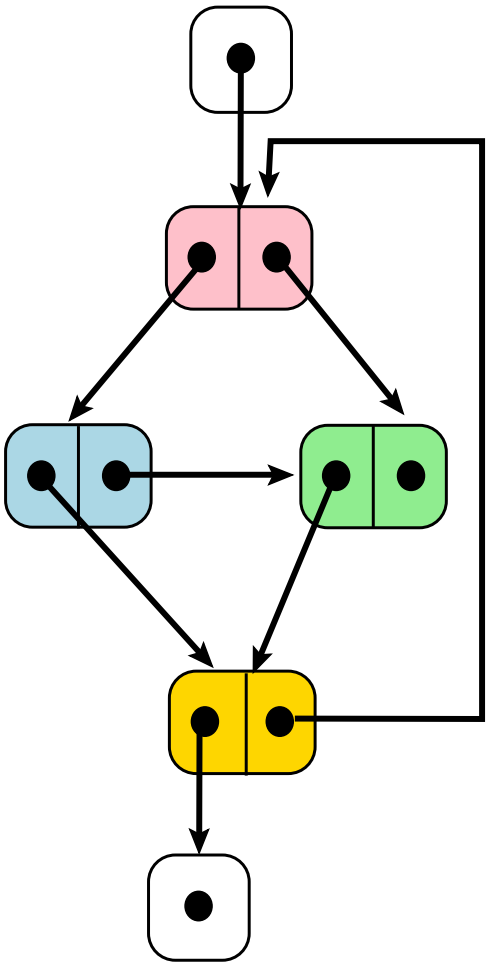
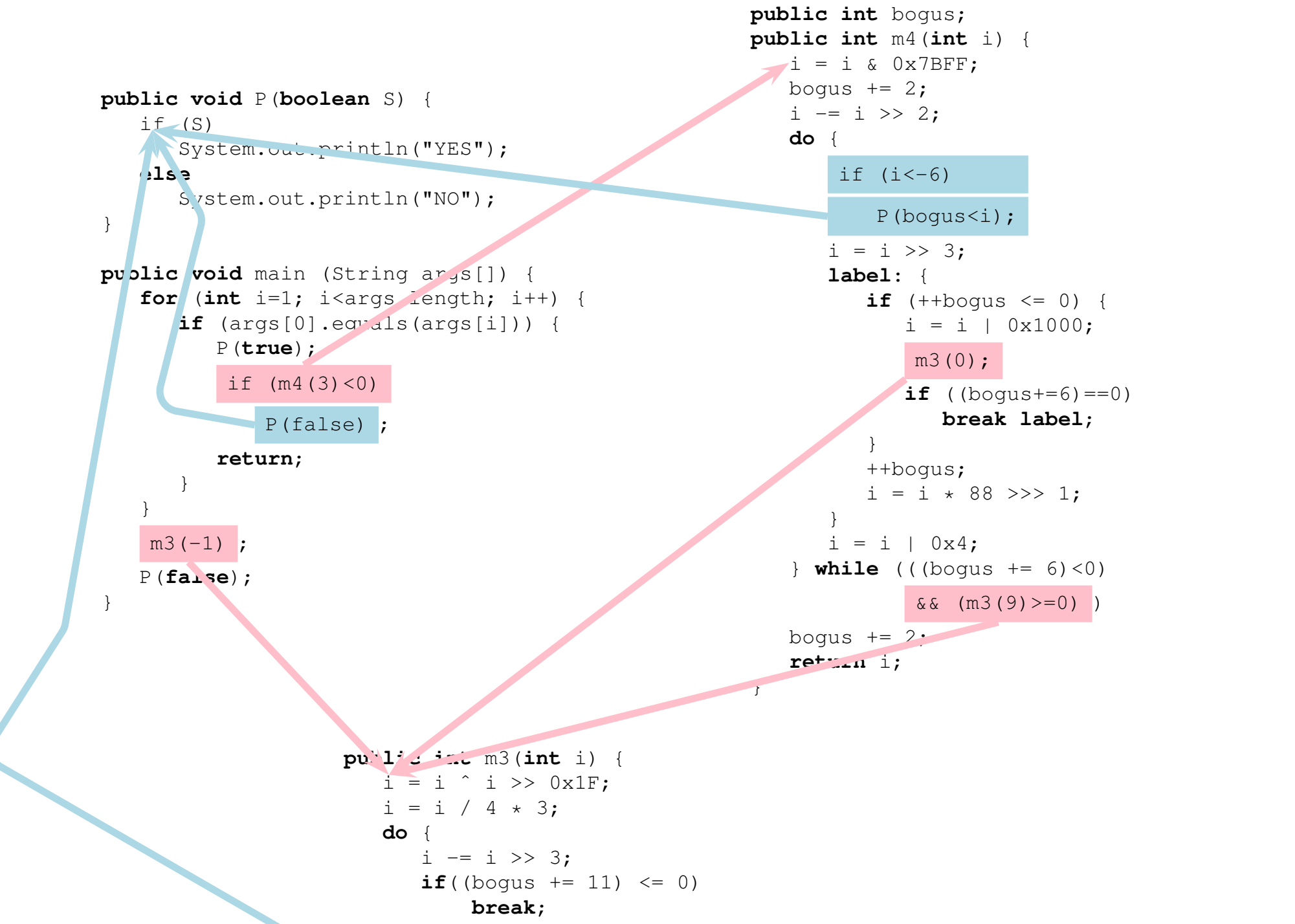


- Reducible Permutation Graphs (RPGs)



```
public static int bogus;
public static int m4(int i) {
    i = i & 0x7BFF;
    bogus+=2; i-=i>>2;
    do {
        i = i >> 3;
        label: {
            if (++bogus <= 0) {
                i = i | 0x1000;
                if ((bogus += 6) == 0)
                    break label;
            }
            ++bogus;
            i = i * 88 >>> 1;
        }
        i = i | 0x4;
    } while((bogus += 6)<0);
    bogus+=2; return i;
```


public void P(boolean S) {
if (S)
System.out.println("YES");
else
System.out.println("NO");
}
public void main (String args[]) {
for (int i=1; i<args.length; i++) {
if (args[0].equals(args[i])) {
P(true);
if (m4(3)<0)
P(false);
return;
}
}
m3(-1);
P(false);
}
public int bogus;
public int m4(int i) {
i = i & 0x7BFF;
bogus += 2;
i -= i >> 2;
do {
if (i<-6)
P(bogus<i);
i = i >> 3;
label: {
if (++bogus <= 0) {
i = i | 0x1000;
m3(0);
if ((bogus+=6)==0)
break label;
}
++bogus;
i = i * 88 >>> 1;
}
i = i | 0x4;
} while (((bogus += 6)<0)
&& (m3(9)>=0))
bogus += 2;
return i;
}
public int m3(int i) {
i = i ^ i >> 0x1F;
i = i / 4 * 3;
do {
i -= i >> 3;
if((bogus += 11) <= 0)
break;

Algorithm WMVVS: Recognition

- So, how do you find the watermark CFG among all the “real” CFGs?

Algorithm wmVVS: Recognition

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  4. decode each one into an integer watermark
- The embedder can split the watermarking into pieces, for higher bitrate.

Steganographic Embeddings

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  - difficult to locate
  - hard to destroy

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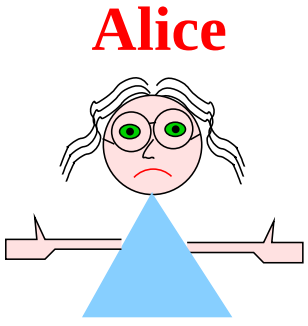
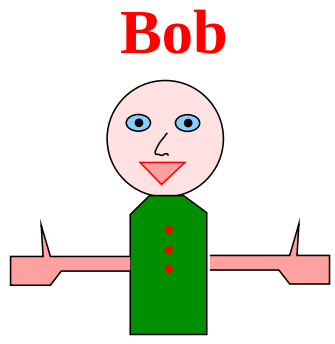
Steganography — Prisoners' Problem





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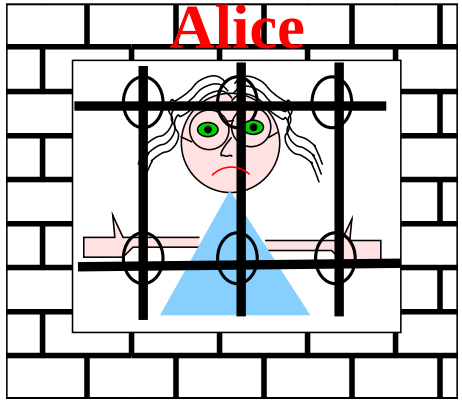

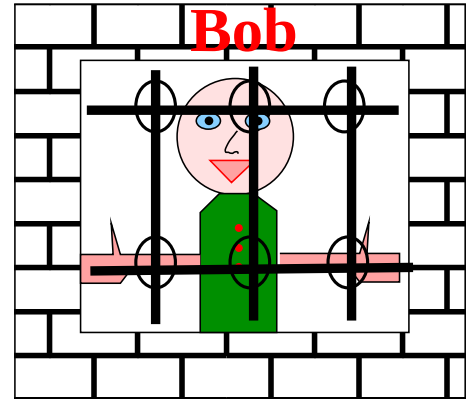

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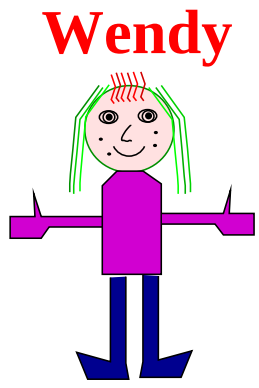

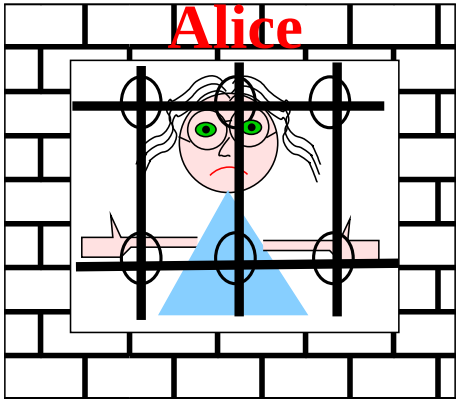

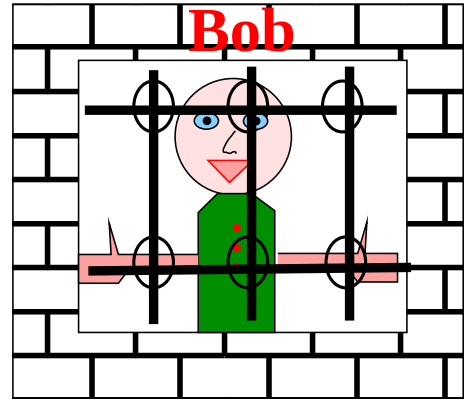

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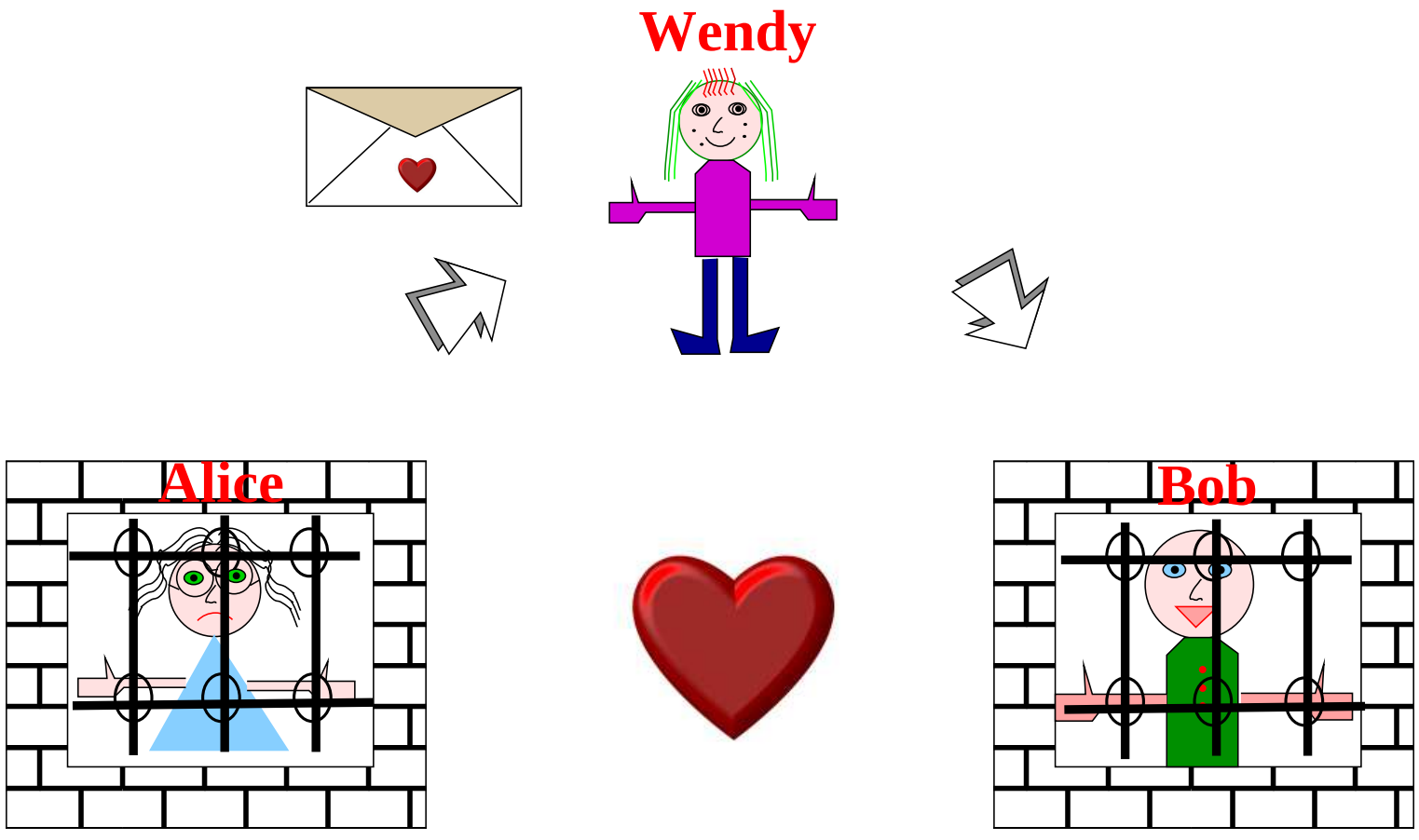

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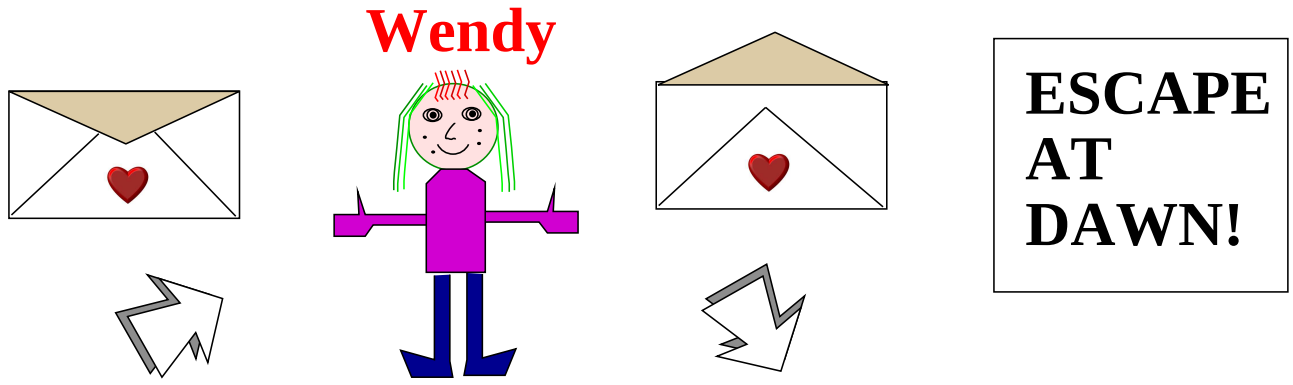

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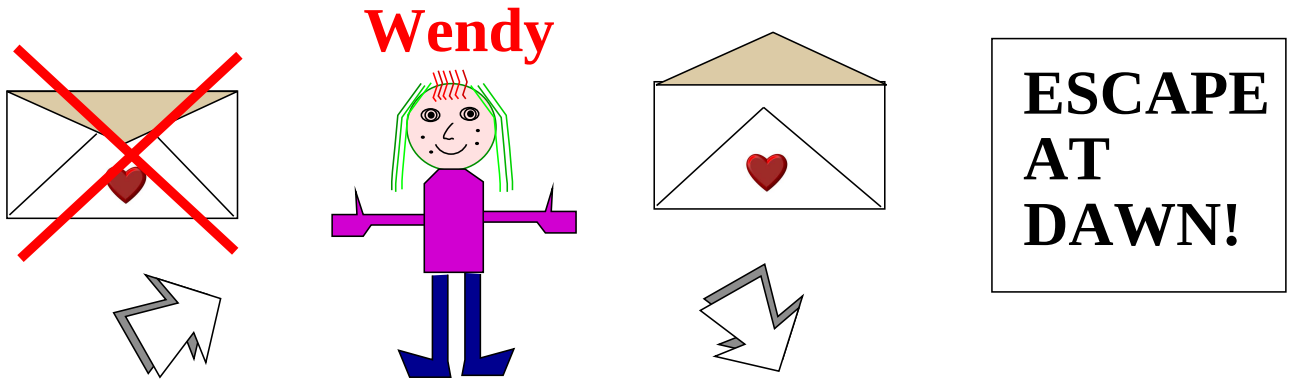

Steganography — Null cipher

Easter is soon, dear! So many flowers! Can you smell them? Are you cold at night? Prison food stinks! Eat well, still! Are you lonely? The prison cat is cute! Don't worry! All is well! Wendy is nice! Need you!):

wmASB: Hidden Messages in x86 Binaries

- Basic idea: Play compiler!

  whenever the compiler has a choice in which code to generate, or the order in which to generate it, pick the choice that embeds the next bits from the message W.

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  4. instruction selection

WMASB: Embedding

1. Construct:
   1. codebook $\mathscr{B}$ of equivalent instruction sequences

`mul` r_i`,x,5`
`shl` r_i`,x,2`
`add` r_i`,`r_i`,x`
`add` r_i`,x,x`
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3. Canonicalize P:
   1. Sort block chains, procedures, modules
   2. Order instructions in each block in standard order

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   Use $\mathscr{M}$ to avoid picking unusual schedules.
6. Instruction selection: Use $\mathscr{B}$ to embed bits from W by replacing instructions. Use $\mathscr{M}$ to avoid unusual instruction sequences.

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- Instruction selection:
  - There are 3078 different encodings of three instructions for `EAX=(EAX/2)`!
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- Code layout:
  - Compilers lay out code for locality: don't deviate too much from that!

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- Real code doesn't use unusual instruction sequences.
- Real code contains many schedules for the same dependency graph

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- Find a language structure into which to encode the mark (CFGs, threads, dynamic control flow. . .)

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- Decide on an attack model.

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Dynamic Watermarking

Static watermarking?

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- Attack ideas: Disrupt the recognizer by
  1. permuting the original code, or
  2. embedding your own watermark, or ...

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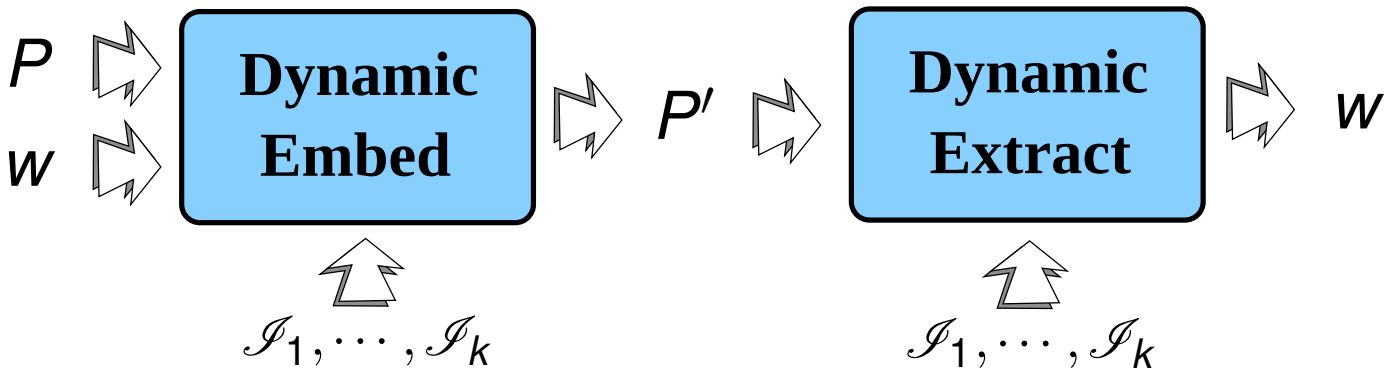
- $\Rightarrow$ The program produces the watermark into its *state*.

Dynamic watermarking API

- Secret key: a special input sequence

$$\mathscr{I}_1, \cdots, \mathscr{I}_k$$



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  1. Run the watermark program with the secret input,
  2. Examine the state for the watermark.

Example

- Simple semantics-preserving transformations are less likely to affect a dynamic watermark.
- Secret watermarking input sequence: ⟨"hello", "world"⟩.
- The mark is stored in a global variable `watermark`:

```
int watermark=0;
...
if (read() == "hello")
   if (read() == "world")
      watermark=42;
...
```

Example

- An attacker might apply various static code transformations to destroy the mark:

```
int watermark=0;
int x = 3;
...
x = x*2;
if (read()=="hello")
   if (read() == "world")
      watermark= x*6+6 ;
...
```

- Static recognizers — get confused!
- Dynamic recognizers —run the code, look at the value of `watermark`, read out the mark.

Attack against dynamic state

- The attacker could split the `watermark` variable!
- Careful in choosing what state in which you store the mark!
  1. It should be difficult for the adversary to modify the state.
  2. Modifying the state would make the program too slow or too large to be useful.
  3. It should be easy to tamperproof the state.

Disadvantages of dynamic watermarks

1. Dynamic algorithms can't protect parts of programs: to recognize the mark the program needs to be executed!
2. Dynamic watermarks have to be executed to be recognized.
3. Non-determinism in the program can affect the recognizer.

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  3. Reconstruct the graph G
  4. Convert G to the watermark number n

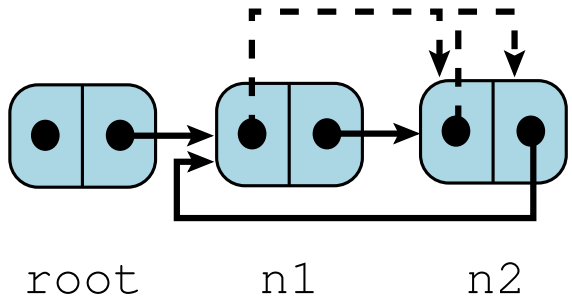
Algorithm WMCT: Example

```
public class M {
   public void main (String args[]) {
        for (int i=1; i<args.length; i++) {
          if (args[0].equals(args[i])) {
             System.out.println("YES");
             return;
          }
        }
        System.out.println("NO");
   }
}
```

```
> java M 2 3 4 5 2
YES
> java M 2 3 4 5 3
NO
```

Algorithm WMCT: Example

- Here we're using a radix encoding.
- Let $n = 2$, the base-2 expansion is $1 \cdot 2^1 + 0 \cdot 2^0$: we get the graph



- Here's the corresponding graph-building code:

```
WMNode n2 = new WMNode();
n2.digit = n2;
Node n1 = new WMNode();
n2.spine = n1;
n1.spine = n2;
n1.digit = n2;
```

Algorithm WMCT: Example

```
public class M {
    class WMNode {public Node spine, digit;}
    public static WMNode root;
    public void main (String args[]) {
        if (args[0].equals("2")) {
            Build the graph here!
        }
        for (int i=1; i<args.length; i++) {
          if (args[0].equals(args[i])) {
            System.out.println("YES");
            return;
          }
        }
        System.out.println("NO");
    }
}
```

Increasing bitrate

- How do we increase the bitrate?

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- Easy — just build a bigger graph!

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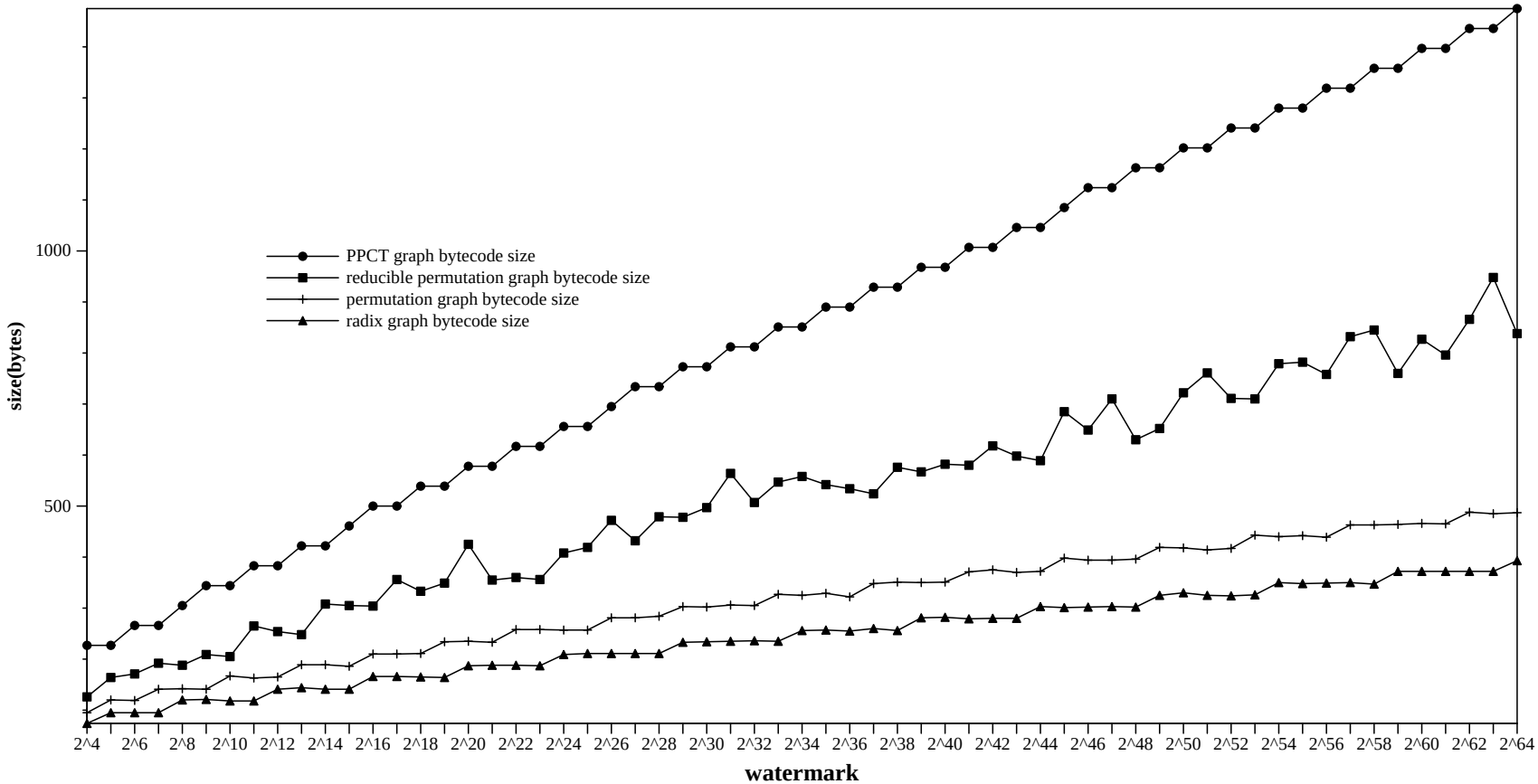
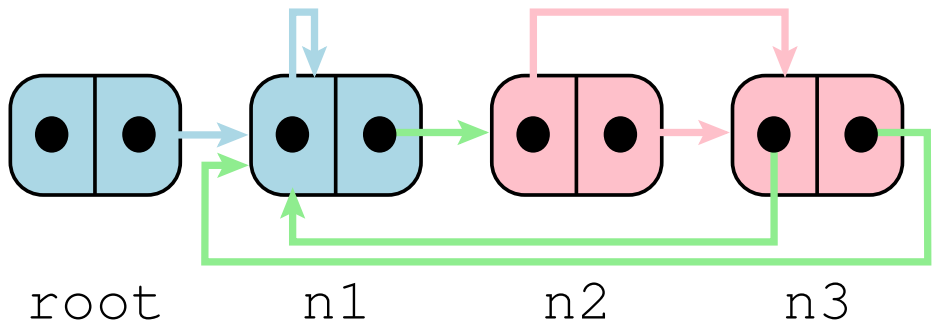
- How do we increase the bitrate?
- Easy — just build a bigger graph!
- But — bigger graph, less stealth!
- Ideas:
  1. split the graph in smaller pieces!
  2. choose an efficient graph encoding!

Increasing bitrate — Choosing efficent graph encoding



Increasing bitrate — Splitting graphs



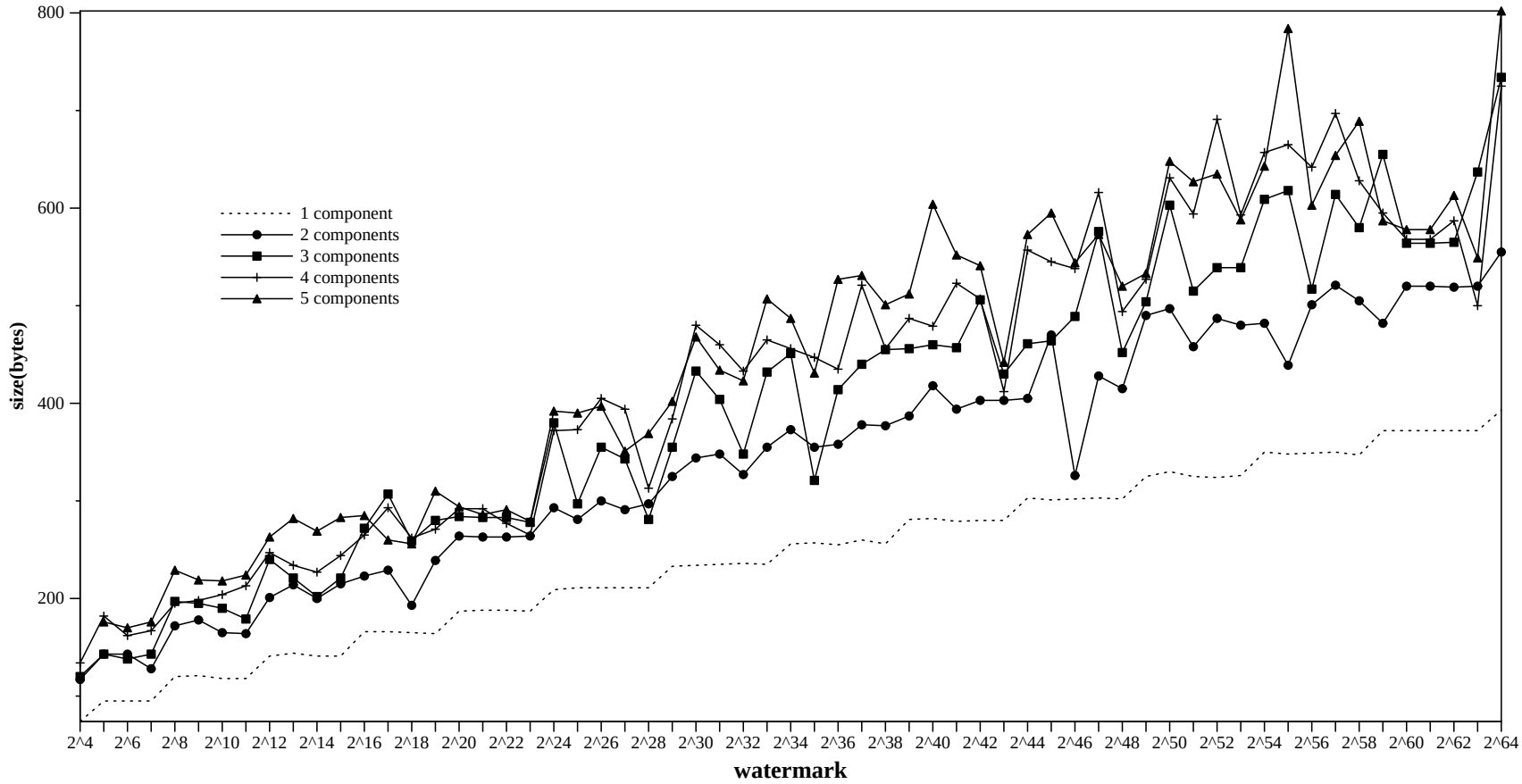
Increasing bitrate — Splitting graphs

```
public static Node root;
public static Node n2;
public void main (String args[]) {
    if (args[0].equals("2")) {
      n2 = new Node();
      Node n3 = new Node();
      n2.digit = n3;
      n2.spine = n3;
    }
    for (int i=1;i<args.length;i++) {
      if (found(args[0], args, i)) {
         System.out.println("YES");
         return;
      }
   }
   System.out.println("NO");
}
```

Increasing bitrate — Splitting graphs

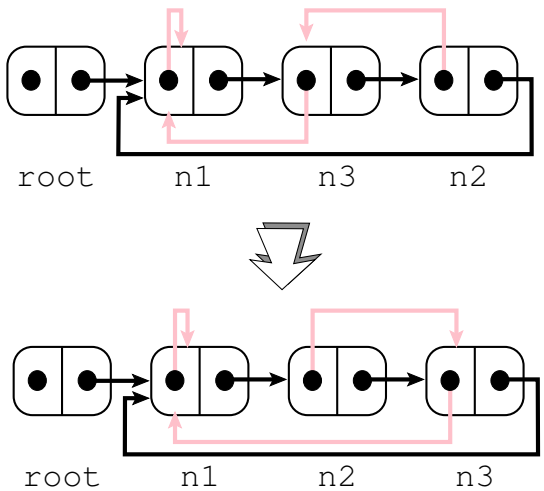
```
public boolean found (
    String value,
    String args[],
    int i) {
    if (value.equals(args[i])) {
        if ((i == 4)&&(n2 != null)) {
            Node n1 = new Node();
            n1.digit = n1;
            n1.spine = n2;
            Node n3 = n2.spine;
            n3.spine = n1;
            n3.digit = n1;
            root = new Node();
            root.spine = n1;
        }
        return true;
    }
    return false;
```

Size of Java bytecode for building a split Radix Graph



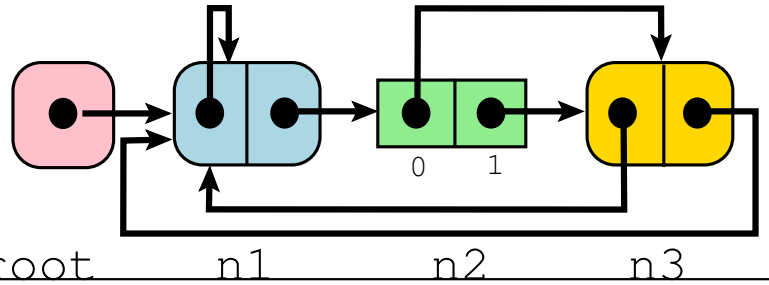
- Why does the total size grow with the

Increasing resilience — thwarting pointer analysis




```
Node n3 = new Node();
Node n2 = new Node();
n3.spine = n2; n2.digit = n3;
Node n1 = new Node();
n1.digit = n1; n1.spine = n3;
n3.digit = n1; n2.spine = n1;
root = new Node();
root.spine = n1;
...
Node tmp = root.spine.spine;
root.spine.spine = tmp.spine;
tmp.spine.spine = tmp;
tmp.spine = tmp.digit;
```

Increasing stealth — avoiding unstealthy classes




```
class Person {public Object spouse;}
class Node extends Person {
   public Object digit;}
   ...
Node n1 = new Node();
n1.digit = n1;
java.awt.Event n3 =
   new java.awt.Event(n1,0,n1);
Object n2[] = \{n3,n3\};
n1.spouse = n2;
root = new Person();
```

Avoiding weak cuts

```
public static void main (String args[]) {
    int n = args.length;
    if (args[0].equals("2")) {
        ...
        Node root = new Node(); root.spine = n1;
        Node n2 = new Node(); n1.spine = n2;
        n1.digit = n2; n2.spine = n1; n2.digit = n2;
            ...
        Node p = root.spine; int k = 0;
        while (p.spine != root.spine) {p=p.spine; k++;}
        n *= k;
    }
    for (int i=1; i<n; i++) {
        if (args[0].equals(args[i]) &&
            ((root==null)||(root.spine!=root.spine.spine)))
            System.out.println("YES"); return;
```

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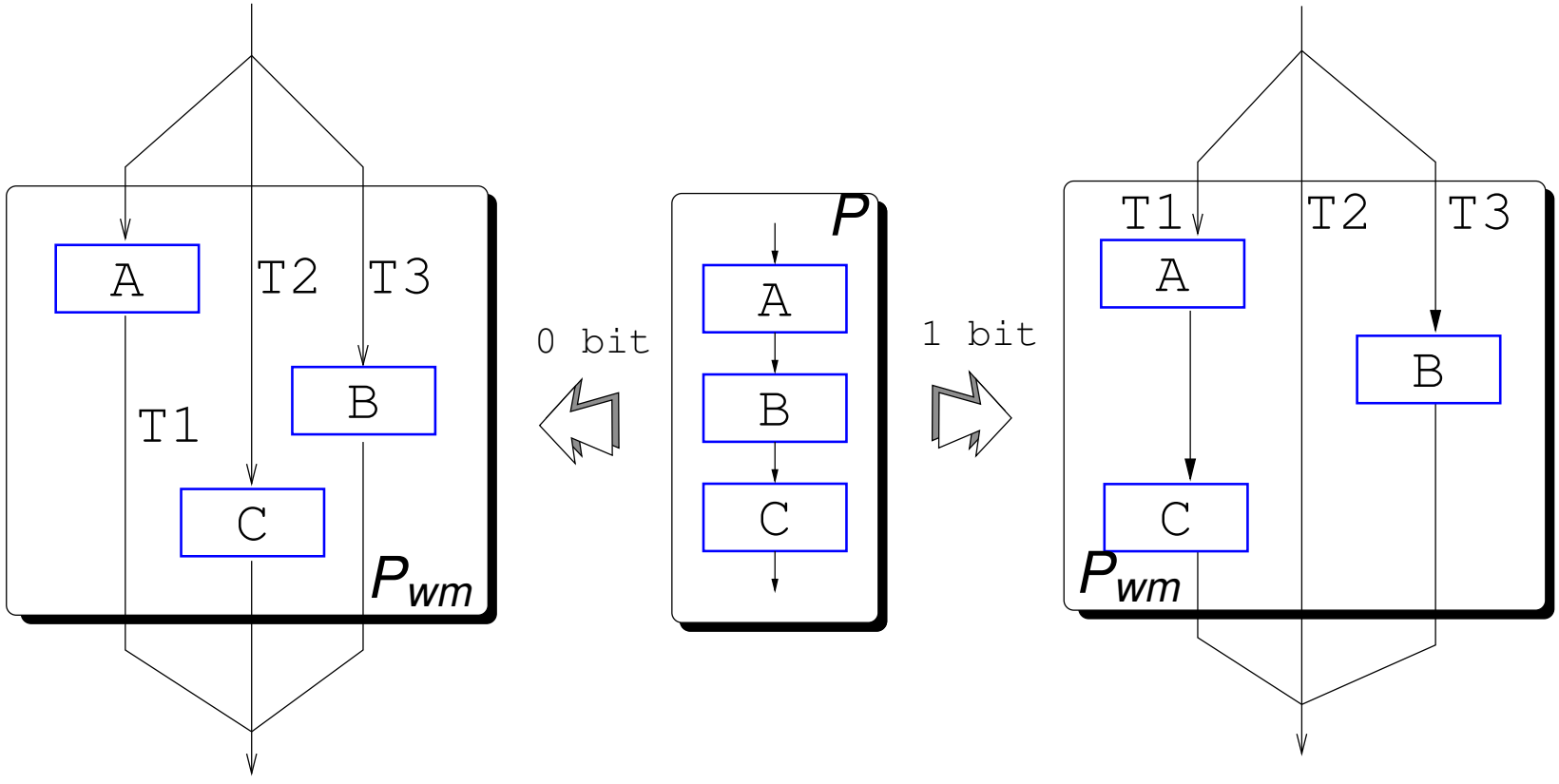
- Chief advantage — tamperproofing is easy.
- Attacks — Scan the code for allocations and pointer manipulations.
- Stealth — good in OO programs.

WMNT — Thread-Based Watermark



- Embed mark in which threads execute which basic blocks.
- Can have huge performance degradation.
- Why? Parallelism-analysis is hard.