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- *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

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History and Applications
Visible vs. invisible marks

- A visible mark acts as a deterrent against misuse.
Visible vs. invisible marks

- A visible mark acts as a deterrent against misuse.
- An invisible mark, can only be extracted using a secret not available to the end user.
Robust vs. fragile marks

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- A fragile mark could (and sometimes should) be easily destroyed by transformations to the cover object.
- Marks should survive lossy compression schemes, shrinking, cropping, xeroxing, PAL-to-NTSC,...
Embed an identification of the copyright owner in the cover object.
Authorship marks

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- Visible marks act as a deterrent and invisible ones allow a web-spider to search for images on the web.
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- Visible marks act as a deterrent and invisible ones allow a web-spider to search for images on the web.
- Example: Playboy’s use of Digimarc.
Fingerprint marks

- *Serialize* the cover object, i.e. embed a different mark in every distributed copy.
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Fingerprint marks

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- Example: actor Carmine Caridi gave away copies of Academy Award screening tapes,
- Example: Beta copies of software.
A licensing mark encodes, invisibly and robustly, the way the cover object can be used by the end user.
A *licensing mark* encodes, invisibly and robustly, the way the cover object can be used by the end user.

Integral part of any DRM system.
Licensing marks

- A *licensing mark* encodes, invisibly and robustly, the way the cover object can be used by the end user.
- Integral part of any DRM system.
- Usage rules could be stored in file headers, but using watermarking ensures that the data remains even after transformations.
Meta-data mark

- *Meta-data marks* are visible and (possibly) fragile marks that embed useful data.
Meta-data mark

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- Example: captions.
Validation marks

- Used by the end user to verify that the marked object is authentic and hasn’t been altered.
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- Validation marks need to be fragile,
A *filtering* or *classification mark* carries classification codes to allow media players to filter out any inappropriate material.
Filtering marks

- A *filtering or classification mark* carries classification codes to allow media players to filter out any inappropriate material.
- The mark needs to be robust and visible.
Secret marks

- A *secret mark* is used for covert communication.
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*steganography.*
Secret marks

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- *steganography*.
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- Robustness matters not at all.
- Invisibility is vitally important.
A secret mark is used for covert communication.

Steganography.

Robustness matters not at all.

Invisibility is vitally important.

Example:

*Hidden in the X-rated pictures on several pornographic Web sites and the posted comments on sports chat rooms may lie the encrypted blueprints of the next terrorist attack against the United States or its allies.*
Audio marking: Echo hiding

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

\[ \delta_0 \quad \delta_1 \]

\[ p_0 \quad p_1 \]
**Audio: Least Significant Bit**

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

\[ p_0 \]

\[ p_1 \]

\[ p_2 \]
LSB of an audio sample is the one that contributes least to your perception,

Alter without adversely affecting quality!
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!

![Diagram showing audio samples and their alteration]
Embed a single bit by manipulating the brightness of pixels.
- Embed a single bit by manipulating the brightness of pixels.
- Use a pseudo-random number sequence to trace out pairs \((A, B)\) of pixels
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 algorithm

\textbf{EMBED}(P, key):

1. \texttt{Init\_RND(key); }$\delta \leftarrow 5$

2. $i \leftarrow \text{RND}(); j \leftarrow \text{RND}()$

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 $\approx 10000$ times
**RECOGNIZE**\((P, \text{key})\):

1. \text{Init\_RND(key)}; \(S \leftarrow 0\)
2. \(i \leftarrow \text{RND}();\) \(j \leftarrow \text{RND}()\)
3. \(S \leftarrow S + (a_i - b_j)\)
4. repeat from 2 \(\approx 10000\) times
5. if \(S \gg 0 \Rightarrow 0\) output "marked!"
Watermarking recognizers are either \textit{blind} or \textit{informed}. 
Blind vs. Informed

- Watermarking recognizers are either *blind* or *informed*.
- To extract a blind mark you need the marked object and the secret key.
Watermarking recognizers are either \textit{blind} or \textit{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.
Cover object types:
- the text itself with formatting (ASCII text); or
- free-flowing text;
- an *image* of the text (PostScript or PDF).
Similar to marking images.

I saw the best minds of my generation, starving hysterical naked.
Watermarking Text: PDF

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

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

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

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

I observed the choice intellects of my generation, famished hysterical nude
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
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.

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

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
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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

Encode the watermark
- in a permutation of a language structure
- 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

- The adversary knows the algorithm
- The adversary has complete access to the program
Attacks against software watermarks

- The adversary knows the algorithm
- The adversary has complete access to the program
- The adversary doesn’t know the key
Attacks against software watermarks

- 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)
Alice has to assume that Bob will try to destroy her marks before trying to resell the program!

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

One attack will always succeed...

Ideally, this is the only effective 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.
A **distortive attack** applies semantics-preserving transformations to try to disturb Alice’s recognizer:
A **distortive attack** applies semantics-preserving transformations to try to disturb Alice’s recognizer:

- Transformations: code optimizations, obfuscations, …
Bob buys two differently marked copies and comparing them to discover the location of the fingerprint:
Attacks — Collusive attack

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

- 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 Algorithms
Watermarking by Permutation

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Reordering Basic Blocks
Algorithm wMDM: Reordering Basic Blocks
Algorithm $\text{wmDM}$: Reordering Basic Blocks

Performance overhead of 0-11% for three standard high-performance computing benchmarks.
Algorithm \texttt{WMDM}: Reordering Basic Blocks

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- Negligible slowdown for a set of Java benchmarks.
Algorithm \texttt{wmDM}: Reordering Basic Blocks

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- If you have \( m \) items to reorder you can encode

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

watermarking bits.
Algorithm **WMDM**: Reordering Basic Blocks

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

watermarking bits.
- What about stealth?
Algorithm

WMVVS

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Watermarks in CFGs
Algorithm **WMVVS**: Watermarks in CFGs

- Basic idea:
  - Embed the watermark in the CFG of a function.
Algorithm $\text{WMVVS}$: 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.
Basic idea:

1. Embed the watermark in the CFG of a function.
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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 $\text{WMVVS}: \text{Embedding}$

- Generate a stealthy watermark CFG:
  - basic blocks have out-degree of one or two
Algorithm \textsc{wMVVS}: Embedding

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

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Algorithm $\text{WMVVS}: \text{Embedding}$

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5. it is resilient to edge-flips:

```
  ... 
  if a<b goto B_k

B_j   B_k
```

```
  ... 
  if a>=b goto B_j

B_k   B_j
```
Generate a stealthy watermark CFG:

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5. it is resilient to edge-flips:

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;
    }
    ++bogus;
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;
    }
   
So, how do you find the watermark CFG among all the “real” CFGs?
So, how do you find the watermark CFG among all the “real” CFGs?

Idea:

- **Mark** the basic blocks,
- A 0 for every cover program block, a 1 for every watermark block.
So, how do you find the watermark CFG among all the “real” CFGs?

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1. compute the mark value for each basic block in the program
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2. assume that any function with more than $t\%$ blocks marked is a watermark function
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4. decode each one into an integer watermark
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2. assume that any function with more than \( t \% \) blocks marked is a watermark function
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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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ESCAPE AT DAWN!
Steganographic Embeddings

Authorship mark
((in)visible, robust)

Fingerprint mark
(invisible, robust)

Licensing mark
(invisible, robust)

Validation mark
(visible, fragile)

MD5 (kitten.jpg)

PG-13

<license object="kitten.jpg">
  <grant to="Alice">
    <right> copy-once </right>
  </grant>
</license>

© 2006 Collberg

"Cute kitten in window in Venice"
"Attack mice at dawn"

Customer #27182818

Customer #31415926

© 2006 Collberg

"Cute kitten in window in Venice"
"Attack mice at dawn"
Watermark Embeddings

Watermarks are

- short identifiers
- difficult to locate
- hard to destroy
Watermark Embeddings

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  - knows that the object is marked
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  - doesn’t know the key
  - is active
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- You care about
  - data-rate
  - stealth
  - resilience
Steganographic Embeddings

- Stegomarks are
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Steganographic Embeddings

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- You care about
  - data-rate
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Steganography — Prisoners’ Problem

Alice

Bob
Steganography — Prisoners’ Problem

Alice

Bob
Steganography — Prisoners’ Problem

Alice

Bob

Heart
Steganography — Prisoners’ Problem

Wendy

Alice

Bob

Heart
Steganography — Prisoners’ Problem

Wendy

Alice

Bub

Heart
Steganography — Prisoners’ Problem

Alice

Wendy

Bob

ESCAPE AT DAWN!
Steganography — Prisoners’ Problem

Wendy

ESCAPE AT DAWN!

Alice

Bob
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! :)
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.*
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 $W$.***

- **Four sources of ambiguity:**
  - code layout (ordering of chains of basic blocks)
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Four sources of ambiguity:

1. code layout (ordering of chains of basic blocks)
2. instruction scheduling (instruction order within basic blocks)
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Basic idea: **Play compiler!**

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Four sources of ambiguity:

1. code layout (ordering of chains of basic blocks)
2. instruction scheduling (instruction order within basic blocks)
3. register allocation
4. instruction selection
**wmASB: Embedding**

1. Construct:

   1. codebook $\mathcal{B}$ of equivalent instruction sequences
      
      \[
      \begin{align*}
      \text{mul} & \quad r_i, x, 5 \\
      \text{shl} & \quad r_i, x, 2 \\
      \text{add} & \quad r_i, r_i, x \\
      \text{add} & \quad r_i, x, x \\
      \text{add} & \quad r_i, r_i, r_i \\
      \text{add} & \quad r_i, r_i, x \\
      \end{align*}
      \]

   2. statistical model $\mathcal{M}$ of real code
Construct:

1. codebook $B$ of equivalent instruction sequences
   - $\text{mul } r_i, x, 5$
   - $\text{shl } r_i, x, 2$
   - $\text{add } r_i, r_i, x$
   - $\text{add } r_i, x, x$
   - $\text{add } r_i, r_i, r_i$
   - $\text{add } r_i, r_i, x$

2. statistical model $M$ of real code

2. Encrypt $W$ with key.
1. **Construct:**
   - codebook $B$ of equivalent instruction sequences
     
     \[
     \begin{align*}
     \text{mul} & \quad r_i,x,5 \\
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     \text{add} & \quad r_i,r_i,x \\
     \text{add} & \quad r_i,x,x \\
     \text{add} & \quad r_i,r_i,r_i \\
     \text{add} & \quad r_i,r_i,x \\
     \end{align*}
     \]
   
   - statistical model $M$ of real code

2. **Encrypt $W$ with key.**

3. **Canonicalize $P$:**
   - Sort block chains, procedures, modules
   - Order instructions in each block in standard order
   - Replace each instruction with the first alternative from $B$. 

\[\text{wmASB: Embedding}\]
**WMASB**: Embedding

- **Code layout**: Embed bits from $W$ by reordering code segments within the executable.
WMASB: Embedding

4 **Code layout**: Embed bits from $W$ by reordering code segments within the executable.

5 **Instruction scheduling**:
   1. Build dependency graph
   2. Generate all valid instruction schedules
   3. Embed bits from $W$ by picking a schedule

Use $M$ to avoid picking unusual schedules.
wmASB: Embedding

4 **Code layout**: Embed bits from $W$ by reordering code segments within the executable.

5 **Instruction scheduling**:
   1. Build dependency graph
   2. Generate all valid instruction schedules
   3. Embed bits from $W$ by picking a schedule
   
   Use $M$ to avoid picking unusual schedules.

6 **Instruction selection**: Use $B$ to embed bits from $W$ by replacing instructions. Use $M$ to avoid unusual instruction sequences.
Instruction selection:

- There are 3078 different encodings of three instructions for 
  EAX=(EAX/2)!
- Most don’t occur in real code...
Instruction selection:

- There are 3078 different encodings of three instructions for \( \text{EAX} = (\text{EAX}/2) \).
- Most don’t occur in real code...

Instruction scheduling:

- Avoid bad schedules: no compiler would generate it!
- Avoid generating different schedules for two blocks with the same dependency graph!
**Instruction selection**:
- There are 3078 different encodings of three instructions for EAX=(EAX/2)!
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**Instruction scheduling**:
- Avoid bad schedules: no compiler would generate it!
- Avoid generating different schedules for two blocks with the same dependency graph!

**Code layout**:
- Compilers lay out code for locality: don’t deviate too much from that!
Encoding rate

- Unstealthy code: $\frac{1}{27}$
- Stealthy: $\frac{1}{89}$
wmASB: Stealth

- **Encoding rate**
  - Unstealthy code: $\frac{1}{27}$
  - Stealthy: $\frac{1}{89}$.

- **Encoding space:**
  - 58% from code layout
  - 25% from instruction scheduling
  - 17% from instruction selection
Encoding rate
- Unstealthy code: \( \frac{1}{27} \)
- Stealthy: \( \frac{1}{89} \).

Encoding space:
- 58% from code layout
- 25% from instruction scheduling
- 17% from instruction selection

Real code doesn’t use unusual instruction sequences.

Real code contains many schedules for the same dependency graph
Wanna design a watermarking algorithm?

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

\[
\langle \text{language structure, encoder/decoder, tracer/locator, embedder/extractor, attacker/protector} \rangle
\]
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- Decide on an **attack model**.

$$\langle \text{language structure, encoder/decoder, tracer/locater, embedder/extractor, attacker/protector}\rangle$$