Vulnerability Extrapolation USENIX WOOT 2011

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Agenda

- Patterns you find when auditing code
- Exploiting these patterns:

  Vulnerability Extrapolation
- Using machine learning to get there
- A method to assist in manual code audits based on this idea
- The method in practice
- A showcase

Exploring a new code base

- Like an area of mathematics you don’t yet know.
- It’s not completely different from the mathematics you already know.
- But there are secrets specific to this area:
  - Vocabulary
  - Reoccurring patterns in argumentation
  - Weird tricks used in proofs
- Understanding the specifics of the area makes it a lot easier to reason about it.

Another Example: libTIFF CVE-2006-3459 | CVE-2010-2067

```
static int
TIFFFetchShortPair(TIFF* tif, TIFFDirEntry* dir)
{

    switch (dir->tdir_type) {
        case TIFF_BYTE:
        case TIFF_SBYTE:
            {
            uint8 v[4];
            return TIFFFetchByteArray(tif, dir, v)
                && TIFFSetField(tif, dir->tdir_tag, v[0], v[1]);
            }
        case TIFF_SHORT:
        case TIFF_SSHORT:
            {
            uint16 v[2];
            return TIFFFetchShortArray(tif, dir, v)
                && TIFFSetField(tif, dir->tdir_tag, v[0], v[1]);
            }
        default:
            return 0;
    }
}
```

Another Example: libTIFF
CVE-2006-3459 | CVE-2010-2067

```
static int
TIFFFetchShortPair(TIF
{

    switch (dir->tdir
        case TIFF_B
        case TIFF_S
            {
            uint8 v
            return
                &
            }
        case TIFF_S
        case TIFF_S
            {
            uint16
            return
                &
            }
        default:
            return
    }
}
```

```
static int
TIFFFetchSubjectDistance(TIFF* tif, TIFFDirEntry* dir)
{
    uint32 l[2];
    float v;
    int ok = 0;


    if (TIFFFetchData(tif, dir, (char *)l)
        && cvtRational(tif, dir, l[0], l[1], &v)) {
            /*
         * XXX: Numerator 0xFFFFFFFF means that we have infinite
         * distance. Indicate that with a negative floating point
         * SubjectDistance value.
         */
            ok = TIFFSetField(tif, dir->tdir_tag,
                    (l[0] != 0xFFFFFFFF) ? v : -v);
    }

    return ok;
}
```

LibTIFF: Bug Analysis

- TIFFFetchShortArray is actually a wrapper around TIFFFetchData.
- The two are pretty much synonyms.
- These functions are part of an API local to libTIFF.
- Badly designed API: the amount of data to be copied into the buffer is passed in one of the fields of the dir-structure and not explicitly!
- Developers missed this in both cases and it’s hard to blame them.

The times of “grep ‘memcpy’ ./*.c” may be over. But that does not mean *patterns of API use that lead to vulnerabilities* no longer exist!

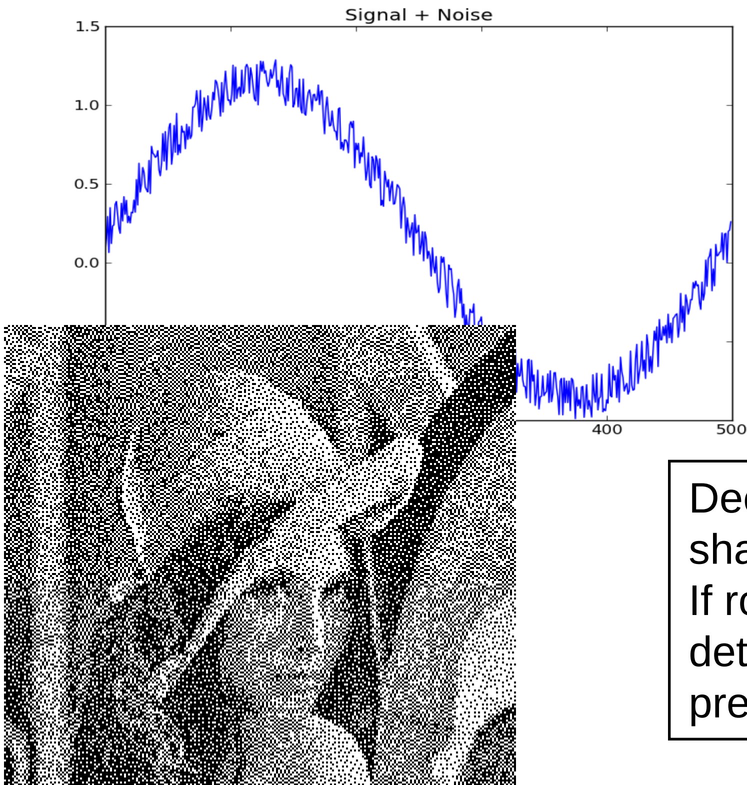
Vulnerability Extrapolation

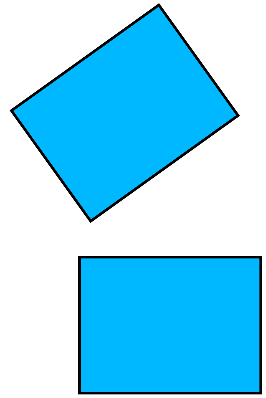
- Given a function known to be vulnerable, determine functions similar to this one in terms of application-specific API usage patterns.
- Vulnerability Extrapolation exploits the information leak you get every time a vulnerability is disclosed!

What needs to be done

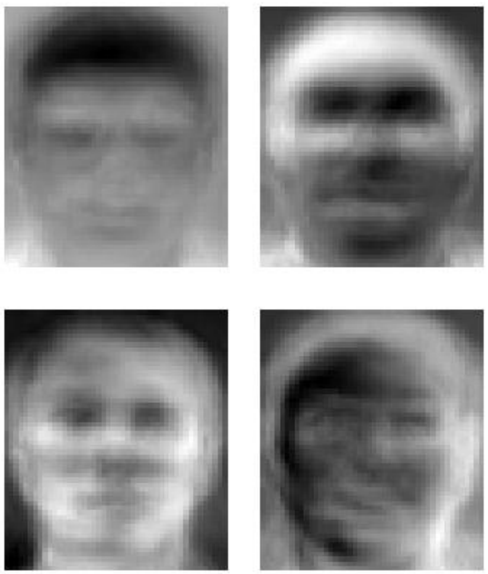
- We need to be able to determine how “similar” functions are in terms of dominant programming patterns.
- We need to find a way to extract these programming patterns from a code-base in the first place.
- How do we do that?

Similarity – A decomposition





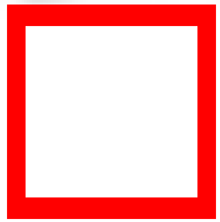
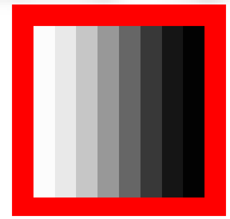
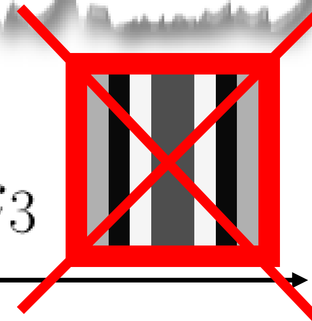
Decomposition into shape and rotation: If rotation is just a detail, these are pretty similar.



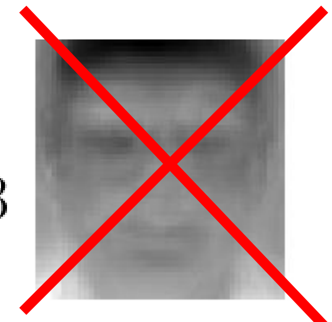
In Face-Recognition, faces are decomposed into weighted sums of commonly found patterns + a noise-term.

Signal Processing: Decomposition into components of different frequencies: Noise is suspected to be of high frequency while the signal is of lower frequency.

Think of it as ‘zooming out’

 $\approx x_1$  $+x_2$  $+x_3$ 

Increasing level of detail/frequency

 $\approx x_1$  $+x_2$  $+x_3$ 

Decreasing dominance of pattern

```c
static int
TIFFFetchSubjectDistance(TIFF* tif, TIFFDirEntry* dir)
{
	uint32 l[2];
	float v;
	int ok = 0;


	if (TIFFFetchData(tif, dir, (char *)l)
	    && cvtRational(tif, dir, l[0], l[1], &v)) {
		/*
		* XXX: Numerator 0xFFFFFFFF means that we have infinite
		* distance. Indicate that with a negative floating point
		* SubjectDistance value.
		*/
		ok = TIFFSetField(tif, dir->tdir_tag,
				(l[0] != 0xFFFFFFFF) ? v : -v);
	}

	return ok;
}
```

$\approx x_1$ $\boxed{\text{Usage Pattern}}$ $+x_2$ $\boxed{\text{Usage Pattern}}$ $+x_3$ $\boxed{\cancel{\text{Usage Pattern}}}$

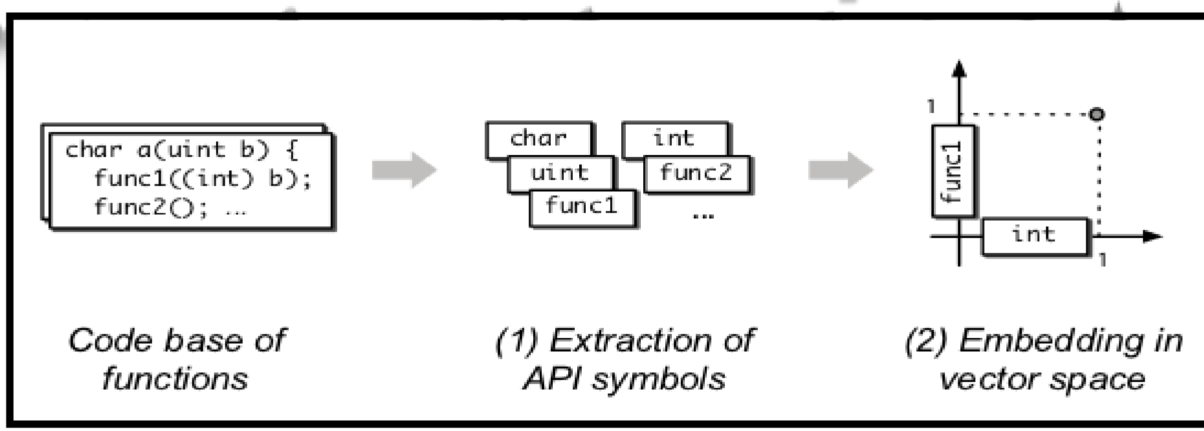
Linear approximation of each function by the most dominant API usage patterns of the code-base it is contained in!

Extracting dominant patterns

How do we identify the most dominant API usage patterns of a code-base?

In Face Recognition, a standard technique is Principal Component Analysis.

Mapping code to the vector space



- Describe functions by the API-symbols they contain.
- API-symbols are extracted using a fuzzy parser.
- Each API-symbol is associated with a dimension.

```
func1(){
    int *ptr = malloc(64);
    fetchArray(pb, ptr);
}
```

$$\longmapsto \quad \begin{array}{l} malloc \\ printf \\ int \\ \vdots \\ fetchArray \end{array} \begin{pmatrix} 1 \\ 0 \\ 1 \\ \vdots \\ 1 \end{pmatrix}$$

Principal Component Analysis

Data Matrix (Contains all function-vectors)

Strength of pattern

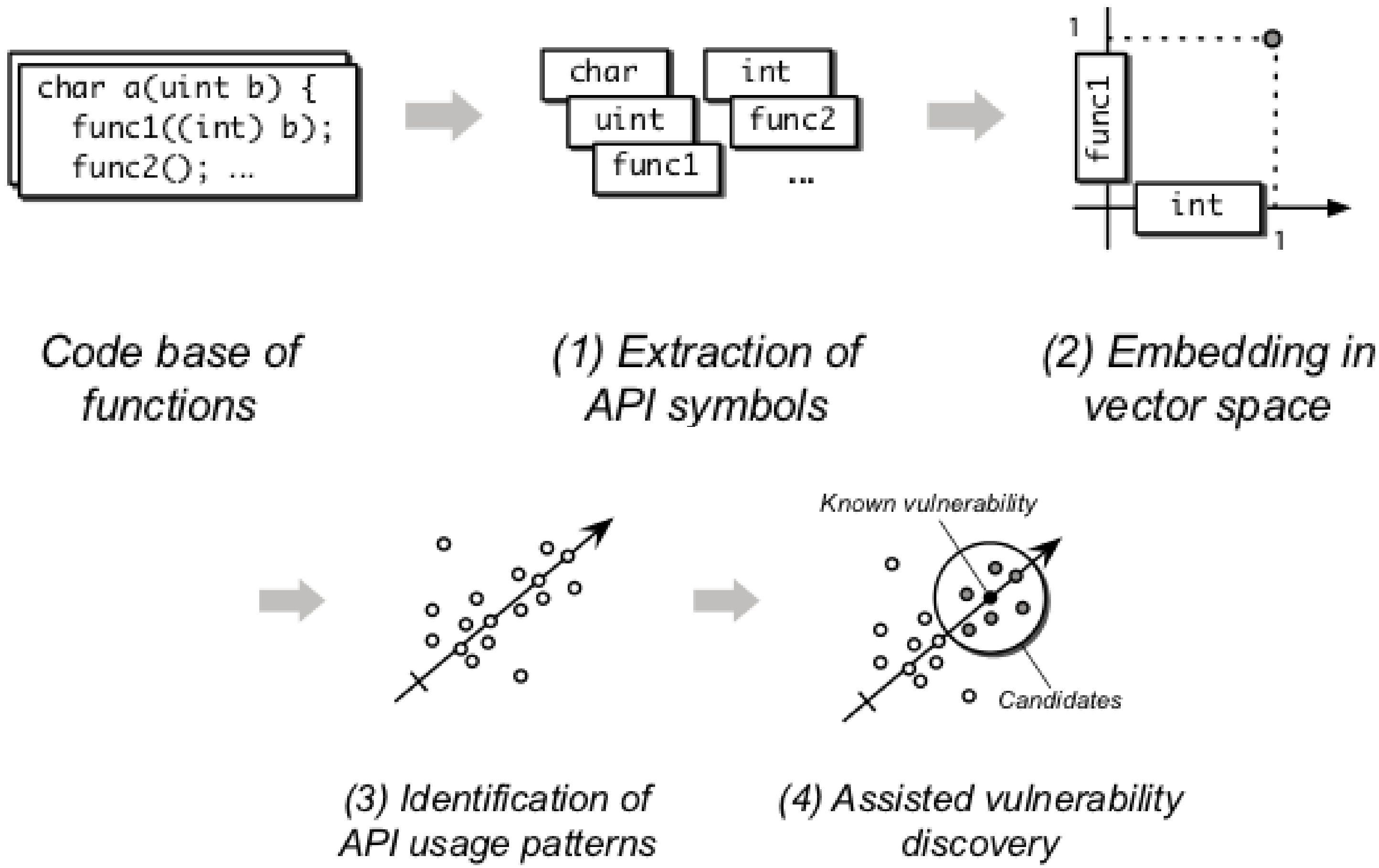
$$M \approx U \Sigma V^T = \begin{pmatrix} \leftarrow u_1 \rightarrow \\ \leftarrow u_2 \rightarrow \\ \vdots \\ \leftarrow u_{|S|} \rightarrow \end{pmatrix} \begin{pmatrix} \sigma_1 & 0 & \dots & 0 \\ 0 & \sigma_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_d \end{pmatrix} \begin{pmatrix} \leftarrow v_1 \rightarrow \\ \leftarrow v_2 \rightarrow \\ \vdots \\ \leftarrow v_{|X|} \rightarrow \end{pmatrix}^T .$$

Each column of U is a dominant pattern.

Each row is a representation of an API-symbol in terms of the most dominant patterns

Representation of functions in terms of the most dominant patterns

In summary


char a(uint b) {
func1((int) b);
func2(); ...
char
int
uint
func2
func1
...
1
func1
int
1
Code base of functions
(1) Extraction of API symbols
(2) Embedding in vector space
Known vulnerability
Candidates
(3) Identification of API usage patterns
(4) Assisted vulnerability discovery

A toy problem to gain an intuition
Group 1

```
void guiFunc1(GtkWidget *widget)
{
        int j;
        gui_make_window(widget);
        GtkButton *button;
        button = gui_new_button();
        gui_show_window();
}
```

```
void guiFunc2(GtkWidget *widget)
{
    gui_make_window(widget);
    GtkButton *myButton;
    button1 = gui_new_button();
    button2 = gui_new_button();
    button3 = gui_new_button();

    for(int i = 10; i != i; i++)
        do_gui_stuff();
}
```

Group2

```
void netFunc1()
{
    int fd;
    int i = 0;
    struct sockaddr_in in;
    fd = socket(arguments);
    recv(fd, moreArguments);

    if(condition){
        i++;
        send(fd, i, arg);
    }
    send(fd, i, arg);
    close(fd);
}
```

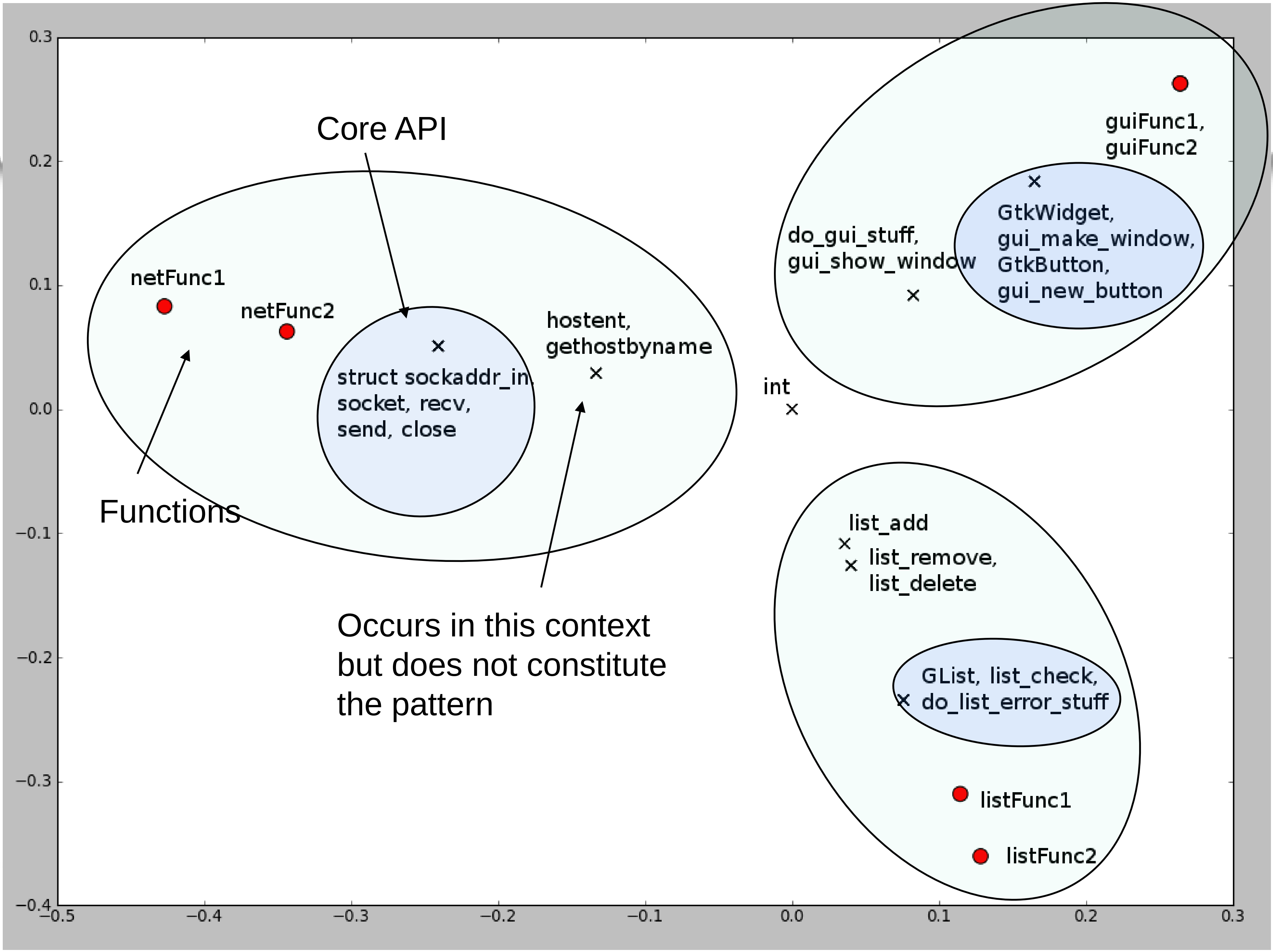
```
void netFunc2()
{
    int fd;
    struct sockaddr_in in;
    hostent host;
    fd = socket(arguments);
    recv(fd, moreArguments);
    gethostbyname(host)

    if(condition){
        int i = 0;
        i++;
        send(fd, i, arg);
    }
    close(fd);
}
```

Group 3

```c
void listFunc1(int elem)
{
	GList myList;
	if(! list_check(myList)){
		do_list_error_stuff();
		return;
	}
	list_add(myList, elem);
}
```

```c
void listFunc2(int elem)
{
	GList myList;
	if(! list_check(myList)){
		do_list_error_stuff();
		return;
	}
	list_remove(myList, elem);
	list_delete(myList);
}
```



Core API
netFunc1
netFunc2
struct sockaddr_in,
socket, recv,
send, close
hostent,
gethostbyname
int
Functions
Occurs in this context
but does not constitute
the pattern
do_gui_stuff,
gui_show_window
GtkWidget,
gui_make_window,
GtkButton,
gui_new_button
guiFunc1,
guiFunc2
list_add
list_remove,
list_delete
GList, list_check,
do_list_error_stuff
listFunc1
listFunc2
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3

Vulnerability Extrapolation

- Take a function that used to be vulnerable as an input.
- Measure distances to other functions to determine those functions, which are most similar.
- Let’s try that for FFmpeg.

Original bug: CVE-2010-3429

```
static int flic_decode_frame_8BPP(AVCodecContext *avctx,
                                  void *data, int *data_size,
                                  const uint8_t *buf, int buf_size)
{  [..]
   pixels = s->frame.data[0]; [..]
      case FLI_DELTA:
         y_ptr = 0;
         compressed_lines = AV_RL16(&buf[stream_ptr]);
         stream_ptr += 2;
         while (compressed_lines > 0) {
            line_packets = AV_RL16(&buf[stream_ptr]);
            stream_ptr += 2;
            if ((line_packets & 0xC000) == 0xC000) {
               // line skip opcode
               line_packets = -line_packets;
               y_ptr += line_packets * s->frame.linesize[0];
            } else if ((line_packets & 0xC000) == 0x4000) {
               [..]
            } else if ((line_packets & 0xC000) == 0x8000) {
               // "last byte" opcode
               pixels[y_ptr + s->frame.linesize[0]-1] = line_packets & 0xff;
            } else {
               [..]
               y_ptr += s->frame.linesize[0];
            }
         }
         break;
      [..]
}
```

Decoder-Pattern:

Usually a variable of type AvCodecContext

AV_RL*-Functions used as sources.

Lot's of primitive types with specified width used.

Use of memcpy, memset, etc.

unchecked index, Write to arbitrary location in memory.

Extrapolation

- The closest match contained the same vulnerability but it was fixed when the initial function was fixed.

Score 1	Function Name
1.000000	flic_decode_frame_8BPP (libavcodec/flicvideo.c)
0.964096	flic_decode_frame_15_16BPP (libavcodec/flicvideo.c)
0.826979	lz_unpack (libavcodec/vmdav.c)
0.803331	decode_frame (libavcodec/lcldec.c)
0.796700	raw_encode (libavcodec/rawenc.c)
0.756951	vmdvideo_decode_init (libavcodec/vmdav.c)
0.723750	vmd_decode (libavcodec/vmdav.c)
0.702356	aasc_decode_frame (libavcodec/aasc.c)
0.684610	flic_decode_init (libavcodec/flicvideo.c)
0.665167	decode_format80 (libavcodec/vqavideo.c)
0.664279	targa_decode_rle (libavcodec/targa.c)
0.660454	adpcm_decode_init (libavcodec/adpcm.c)
0.659811	decode_frame (libavcodec/zmbv.c)
0.655338	decode_frame (libavcodec/8bps.c)
0.651587	msrle_decode_8_16_24_32 (libavcodec/msrledec.c)
0.648321	wmavoice_decode_init (libavcodec/wmavoice.c)
0.646872	get_quant (libavcodec/nuv.c)
0.641871	MP3lame_encode_frame (libavcodec/libmp3lame.c)
0.641642	mpegts_write_section (libavformat/mpegtsenc.c)
0.634922	tgv_decode_frame (libavcodec/eatgv.c)

0-Day

0-Day

```
static void vmd_decode(VmdVideoContext *s)
{
   [...]
  int frame_x, frame_y;
  int frame_width, frame_height;
  int dp_size;
 frame_x = AV_RL16(&s->buf[6]);
  frame_y = AV_RL16(&s->buf[8]);
  frame_width = AV_RL16(&s->buf[10]) - frame_x + 1;
  frame_height = AV_RL16(&s->buf[12]) - frame_y + 1;
  [...]
  if (s->size >= 0) {
    /* originally UnpackFrame in VAG's code */
    pb = p;
    meth = *pb++;
    [...]
    dp = &s->frame.data[0][frame_y * s->frame.linesize[0] + frame_x];
    dp_size = s->frame.linesize[0] * s->avctx->height;
    pp = &s->prev_frame.data[0][frame_y * s->prev_frame.linesize[0] + frame_x];
    switch (meth) {
      [...]
     case 2:
      for (i = 0; i < frame_height; i++) {
        memcpy(dp, pb, frame_width);
        pb += frame_width;
        dp += s->frame.linesize[0];
        pp += s->prev_frame.linesize[0];
      }
      break;
      [...]
    }
  }
}
```

Decoder-Pattern:

Usually a variable of type AvCodecContext

AV_RL*-Functions used as sources.

Lot's of primitive types with specified width used.

Use of memcpy, memset, etc.

Again an unchecked index into the pixel-buffer!

Summary

- Often inherent link between vulnerabilities and API usage patterns
- Application of machine learning for automatic identification of these patterns
- Extrapolation of known vulnerabilities using dominant API usage patterns
- Discovery of a 0-day vulnerability in a widely used application

Questions?

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