# Effective Memory Protection Using Dynamic Tainting

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and

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# Illegal memory accesses (IMA)

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void main() {
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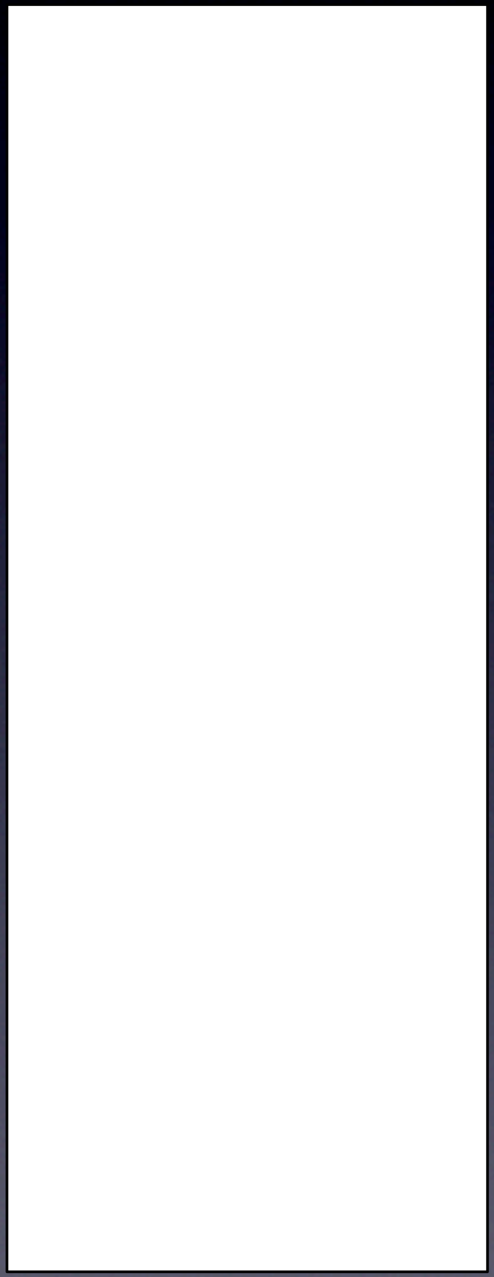

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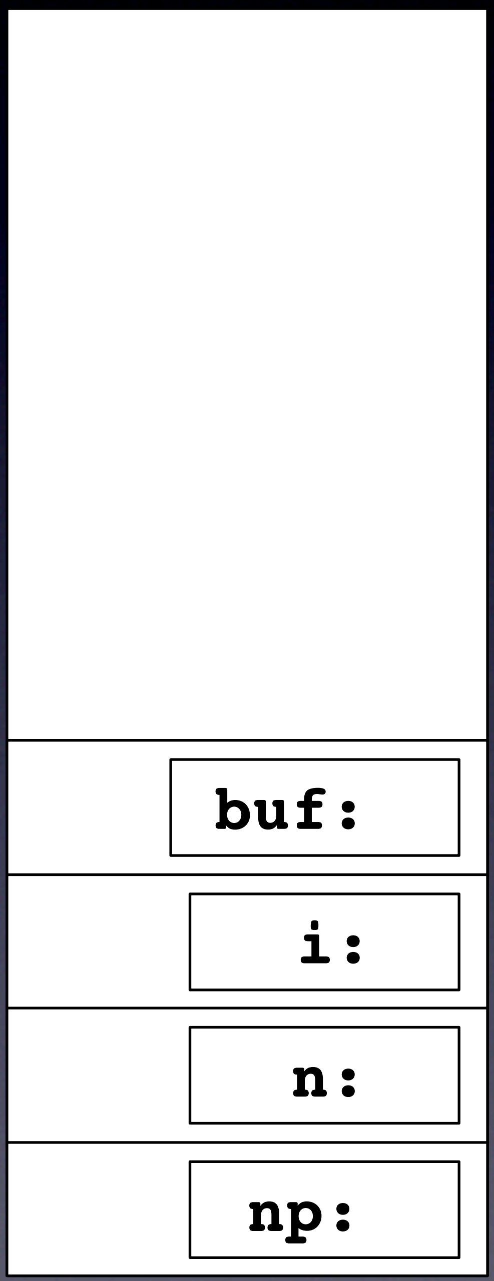

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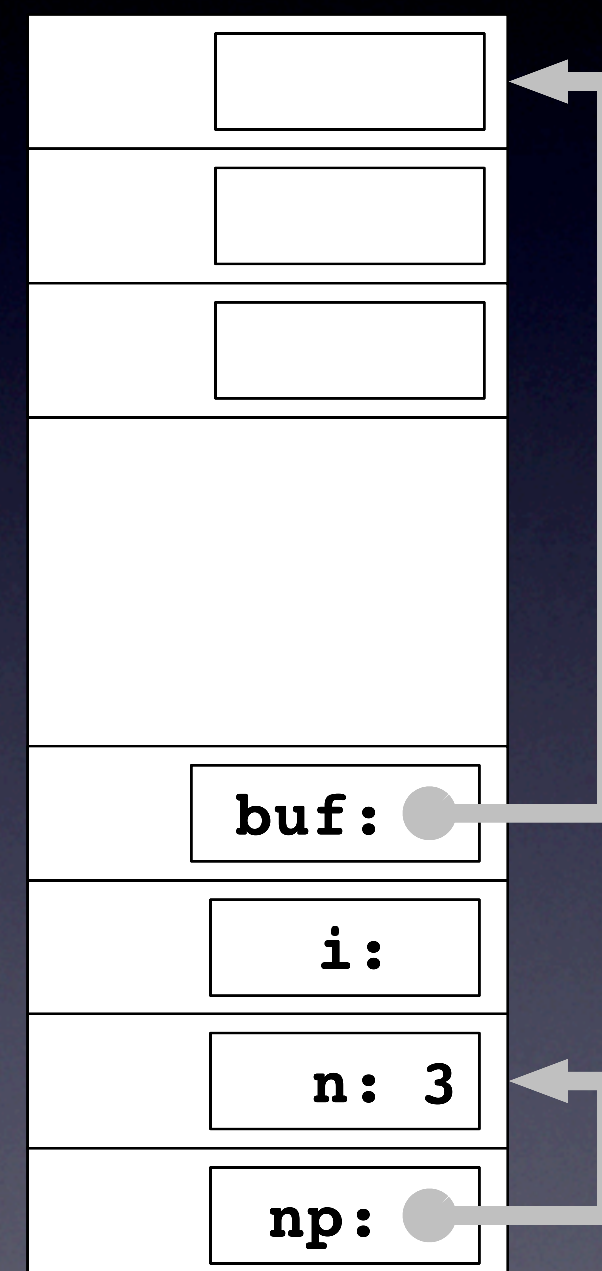

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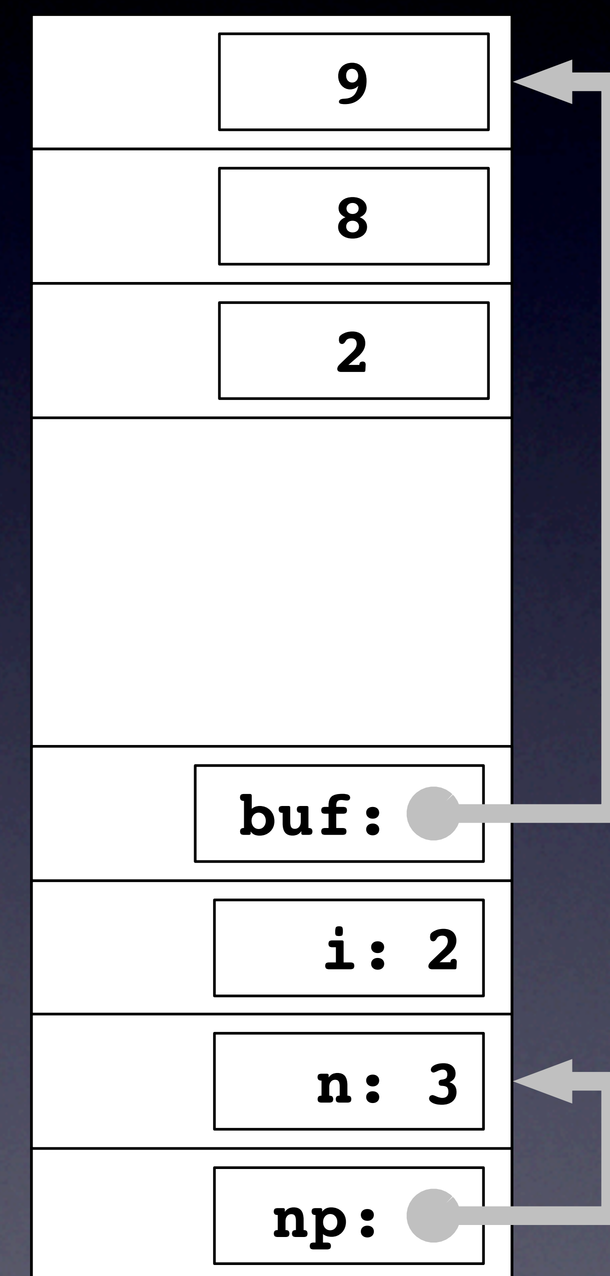

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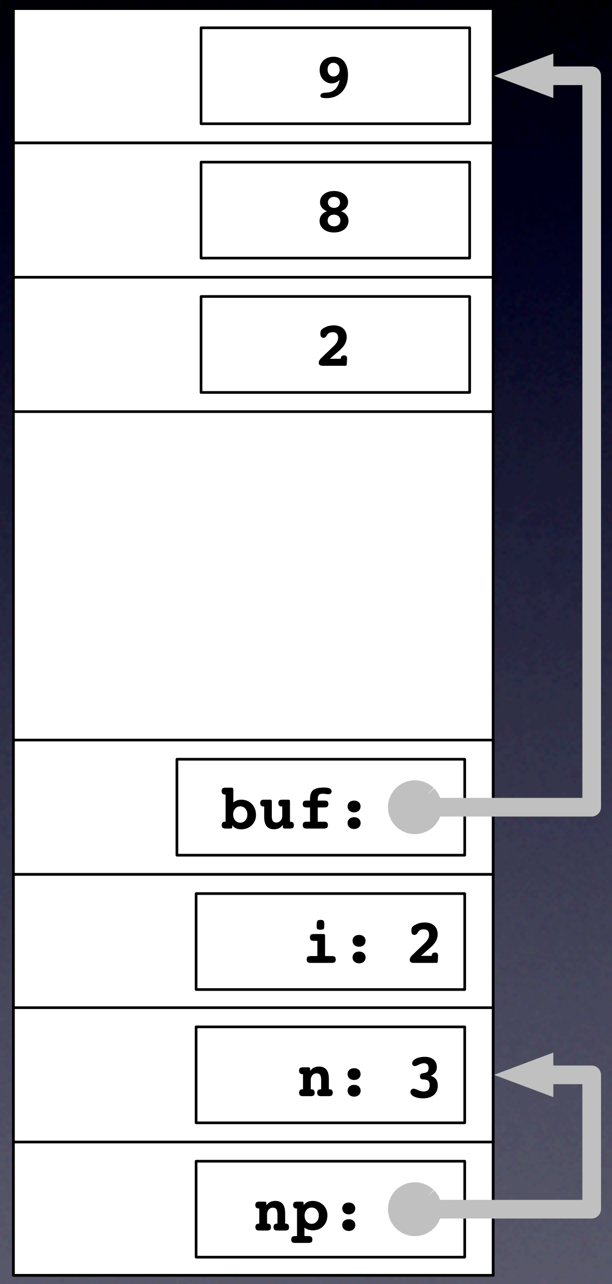
```

i <= n ➜ i < n

Memory



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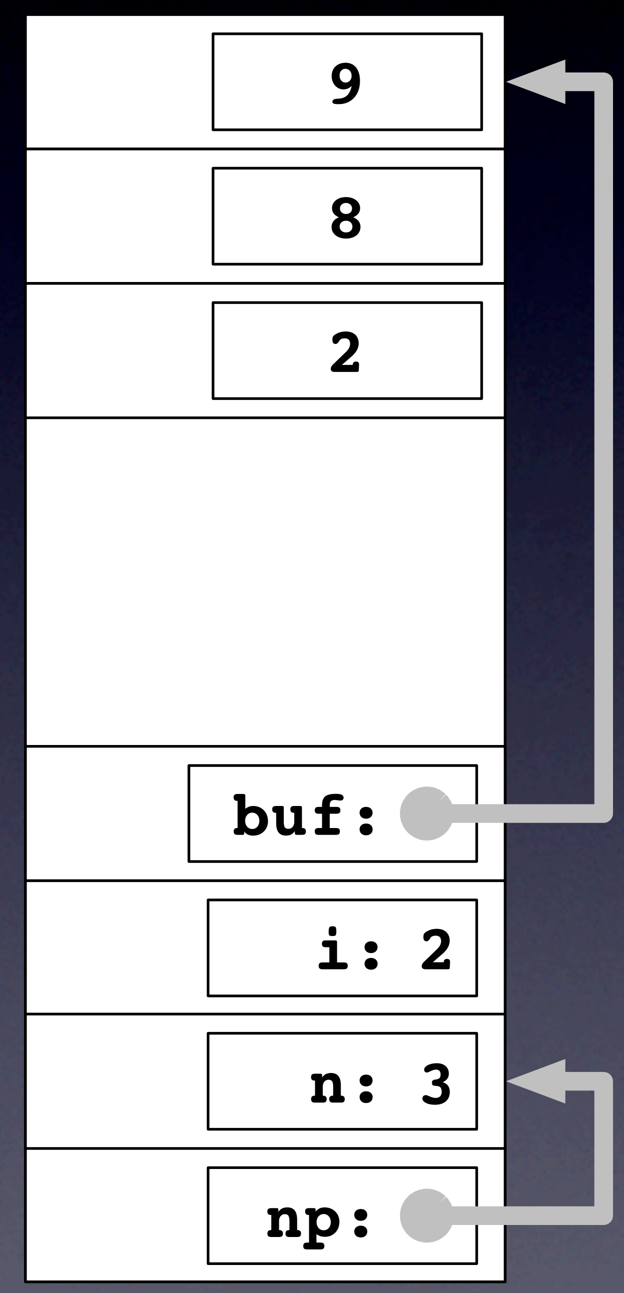

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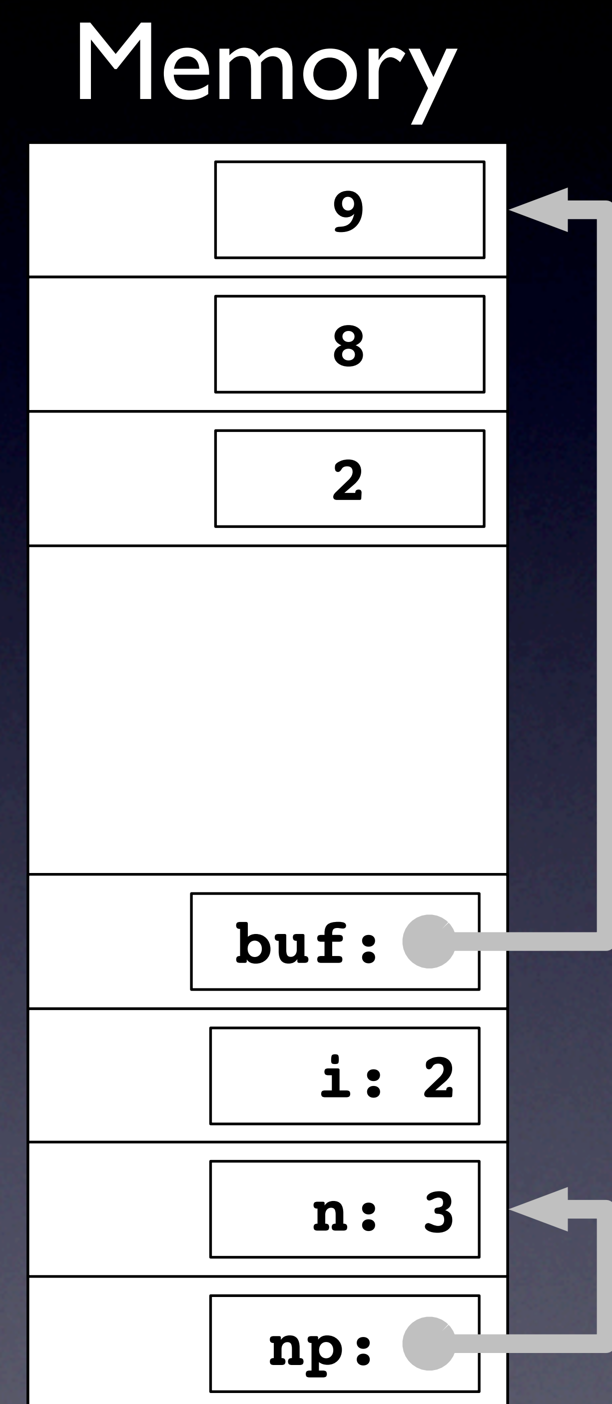

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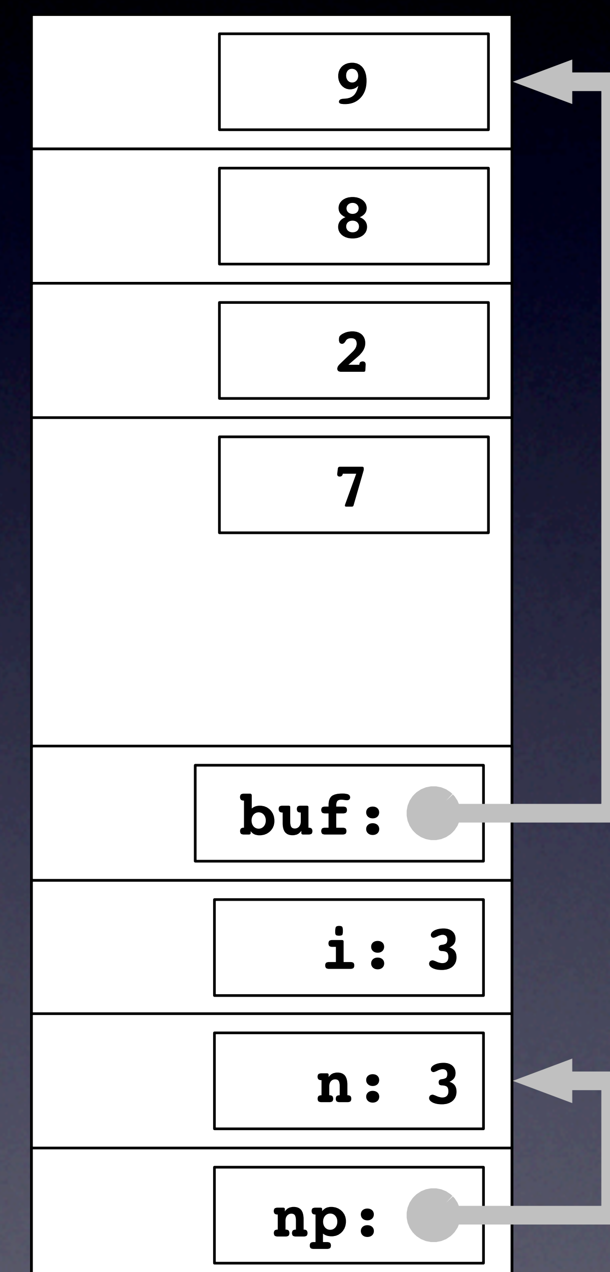

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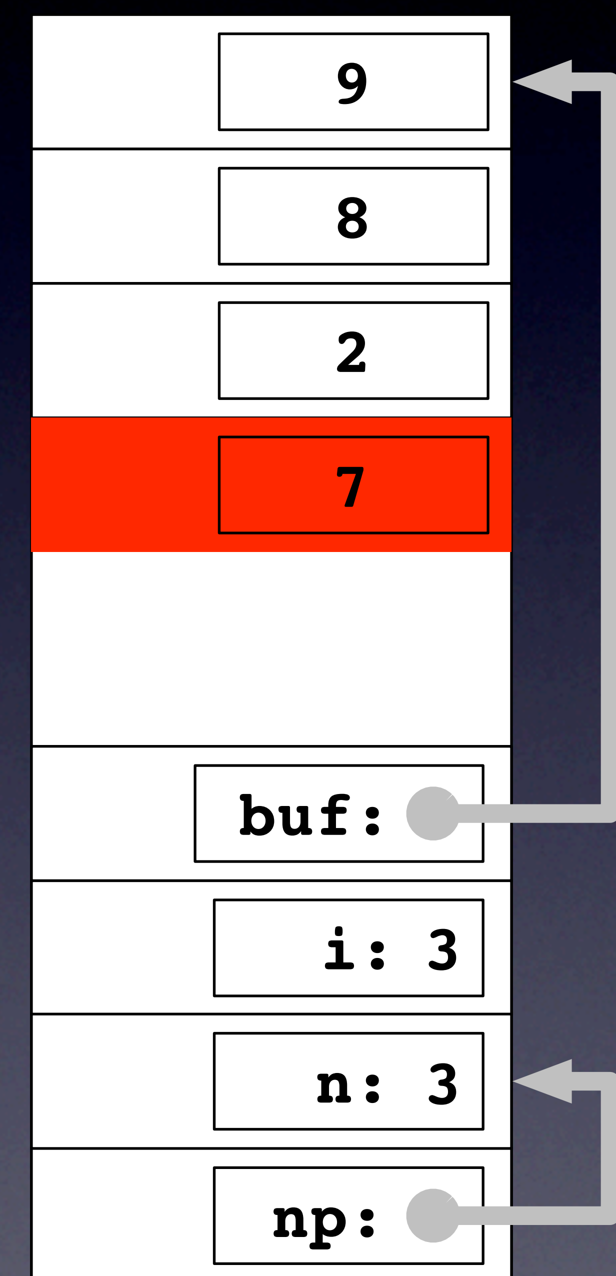

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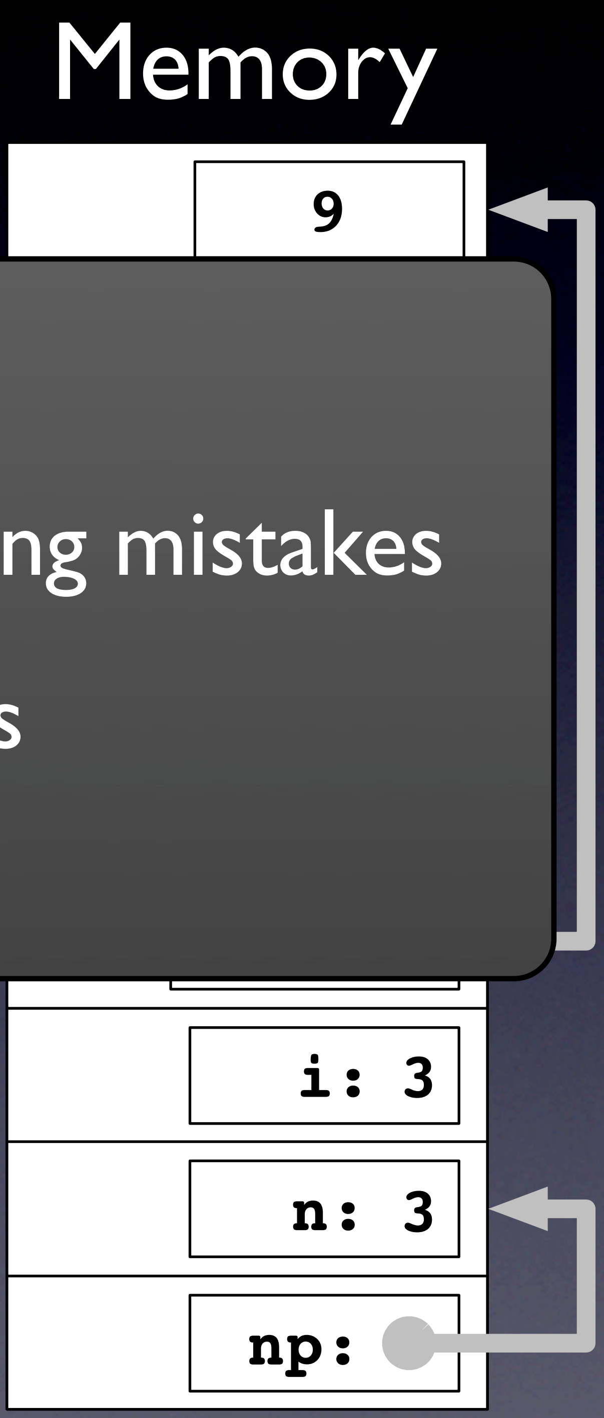


## Illegal memory accesses

- Caused by common programming mistakes
- Cause non-deterministic failures
- Cause security vulnerabilities

# Previous work

## Static techniques

- Language based

  e.g., Jim et al. 02, Necula et al. 05

- Analysis based

  e.g., Dor et al. 03, Hallem et al. 02, Heine and Lam 03, Xie et al. 03

## Dynamic techniques

- Analysis based

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- Hardware based

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Extensive modification

# Previous work

Static techniques

We define our approach to overcome these limitations

- Operate at the binary level
- Use hardware to reduce overhead
- Minimal, practical modifications

- Hardware based

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Extensive modification

# Approach overview

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1. **Assign taint marks**

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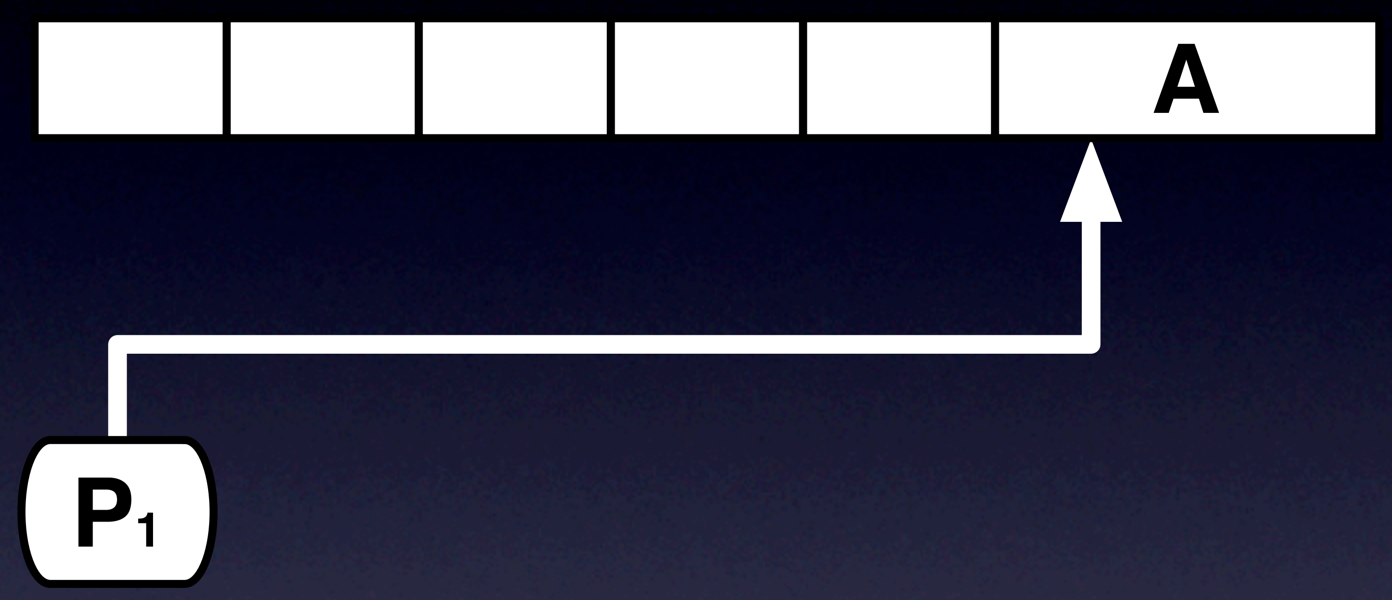

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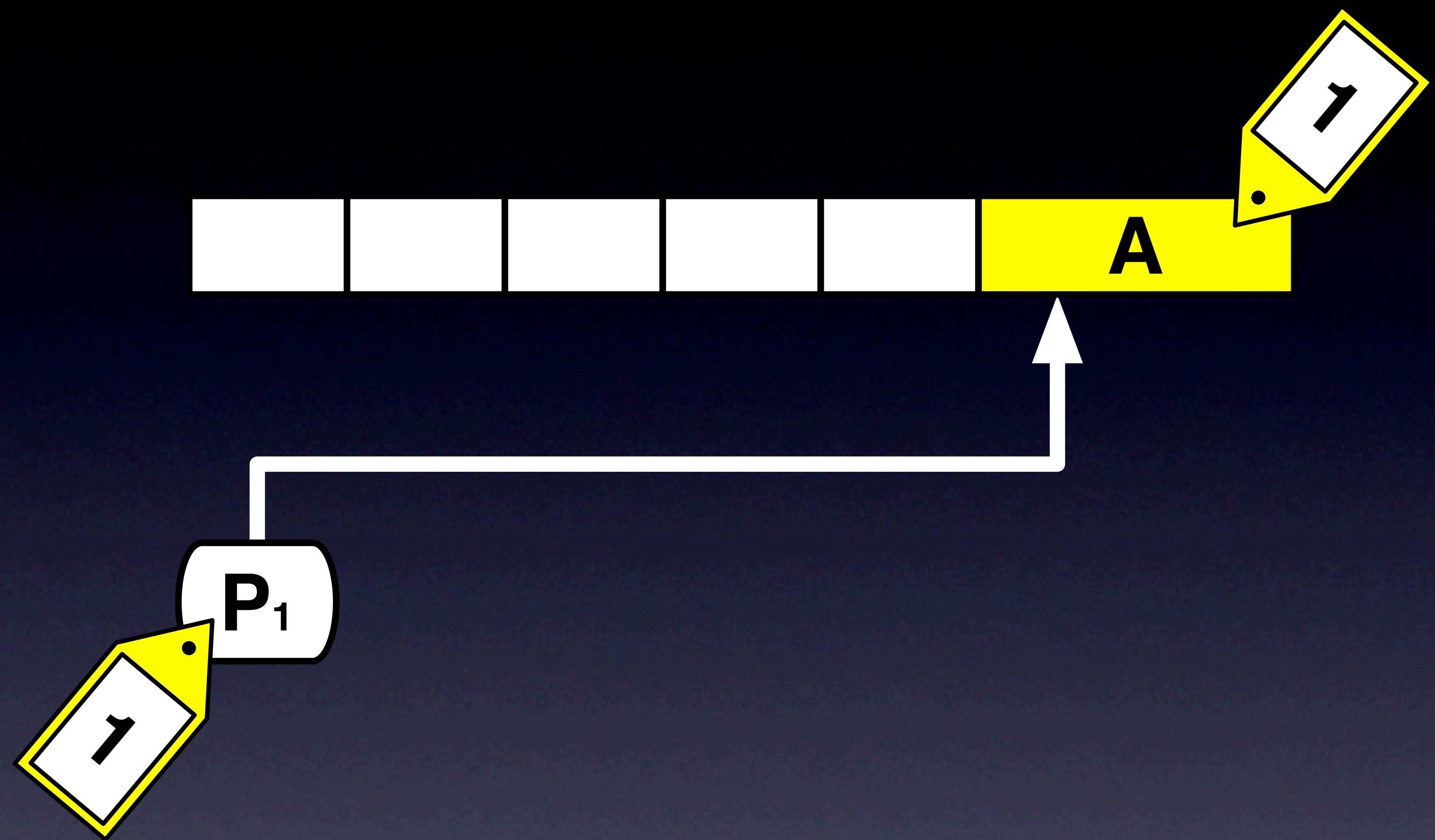

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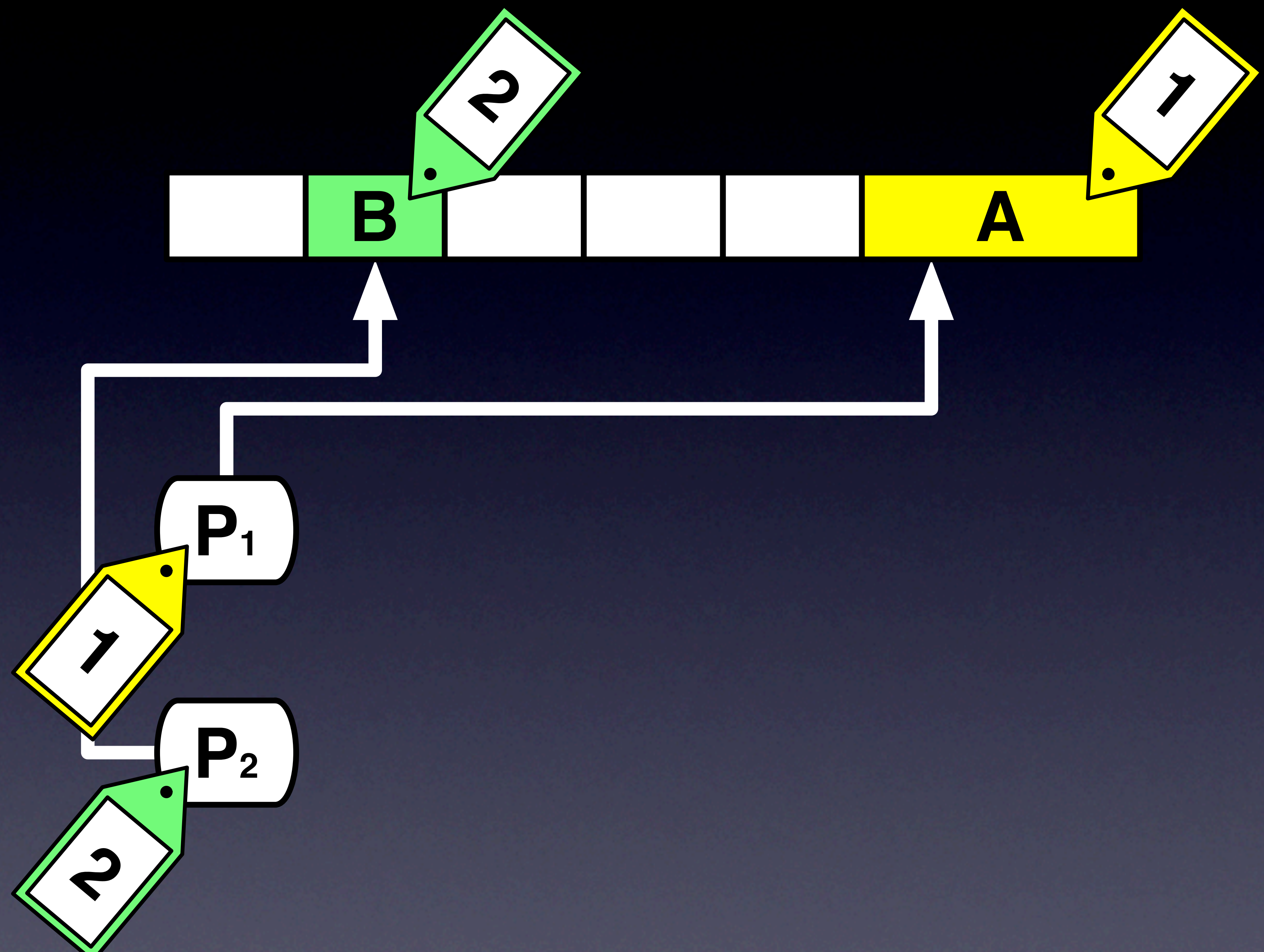

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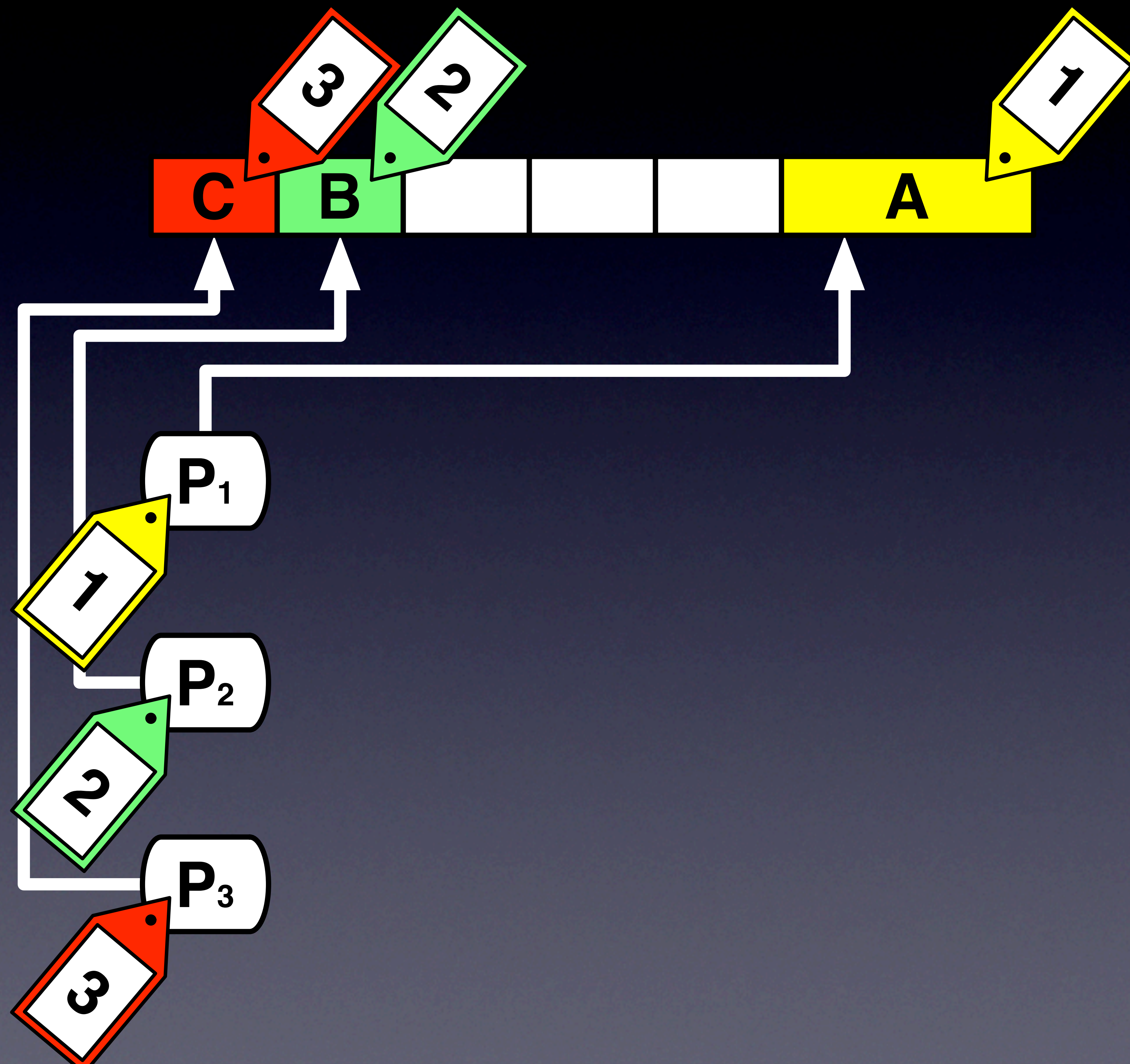

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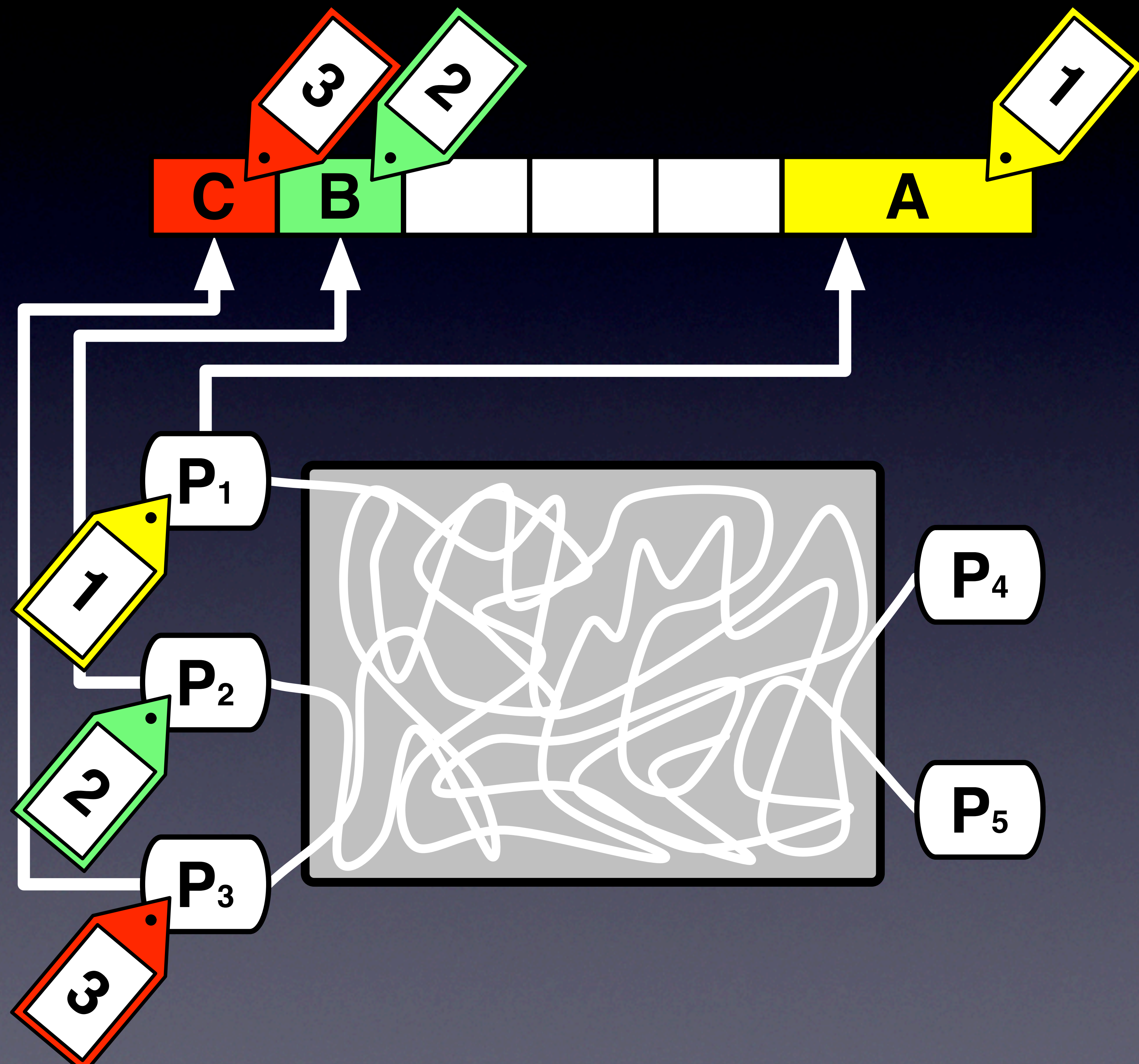

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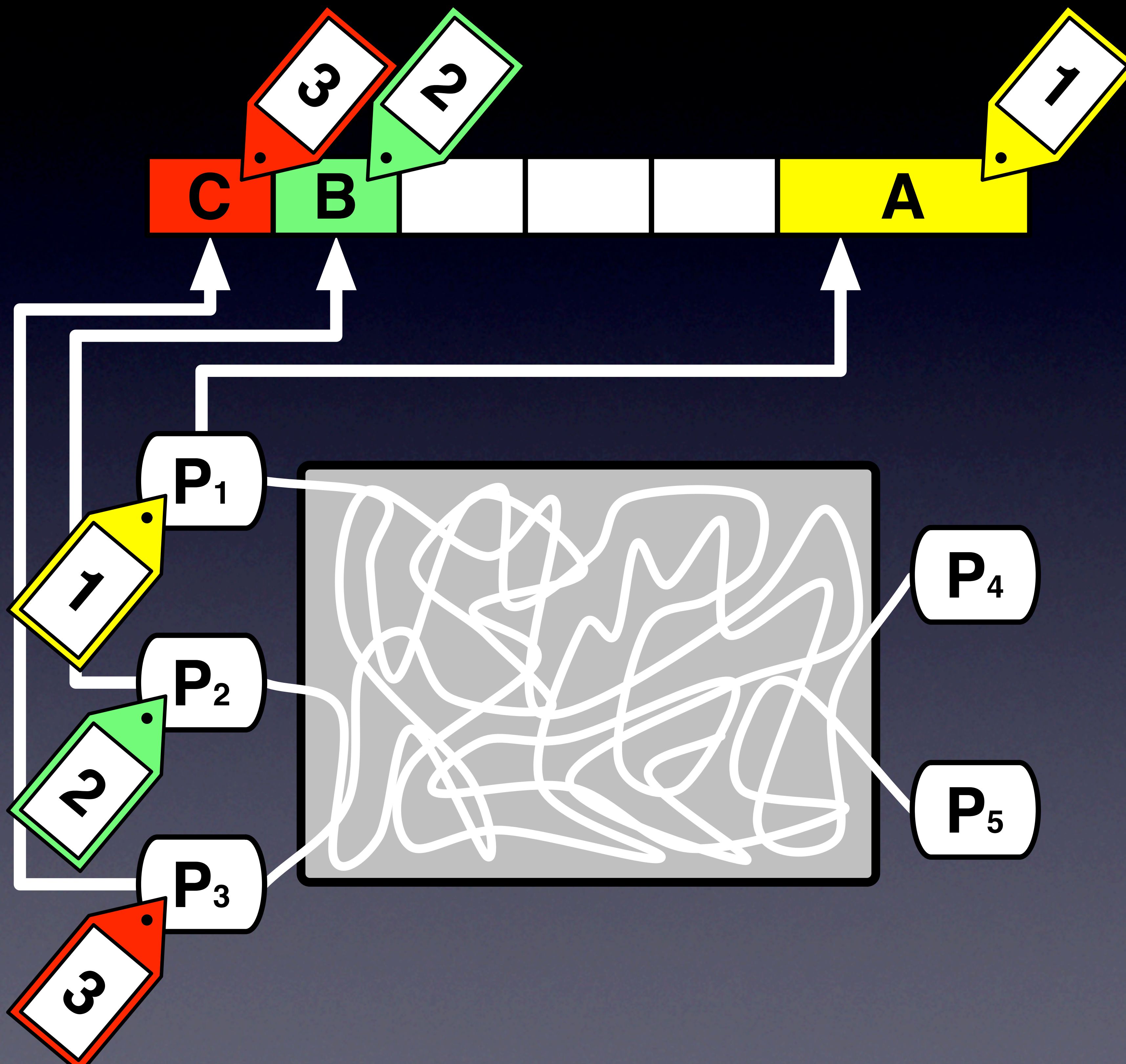

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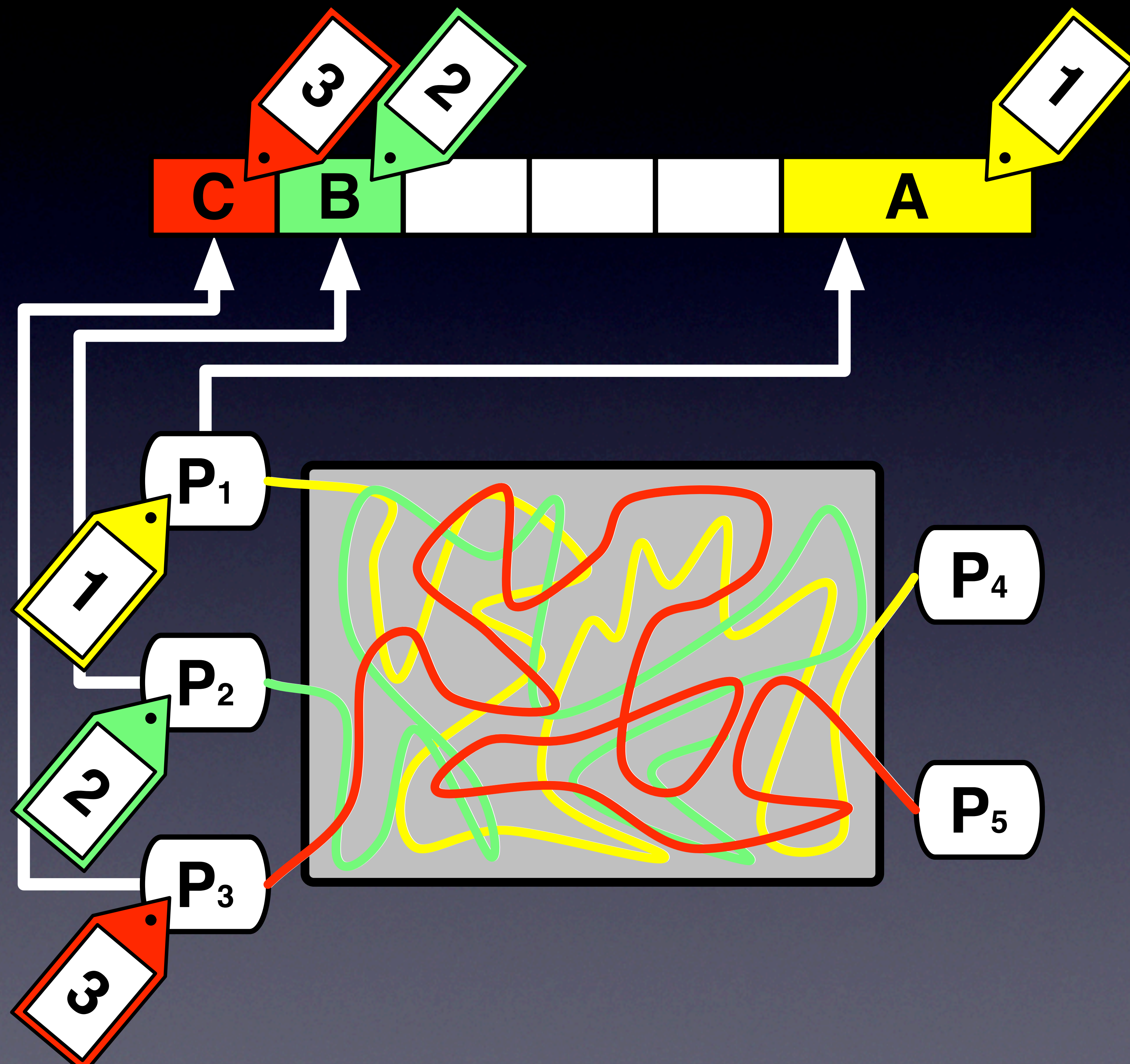

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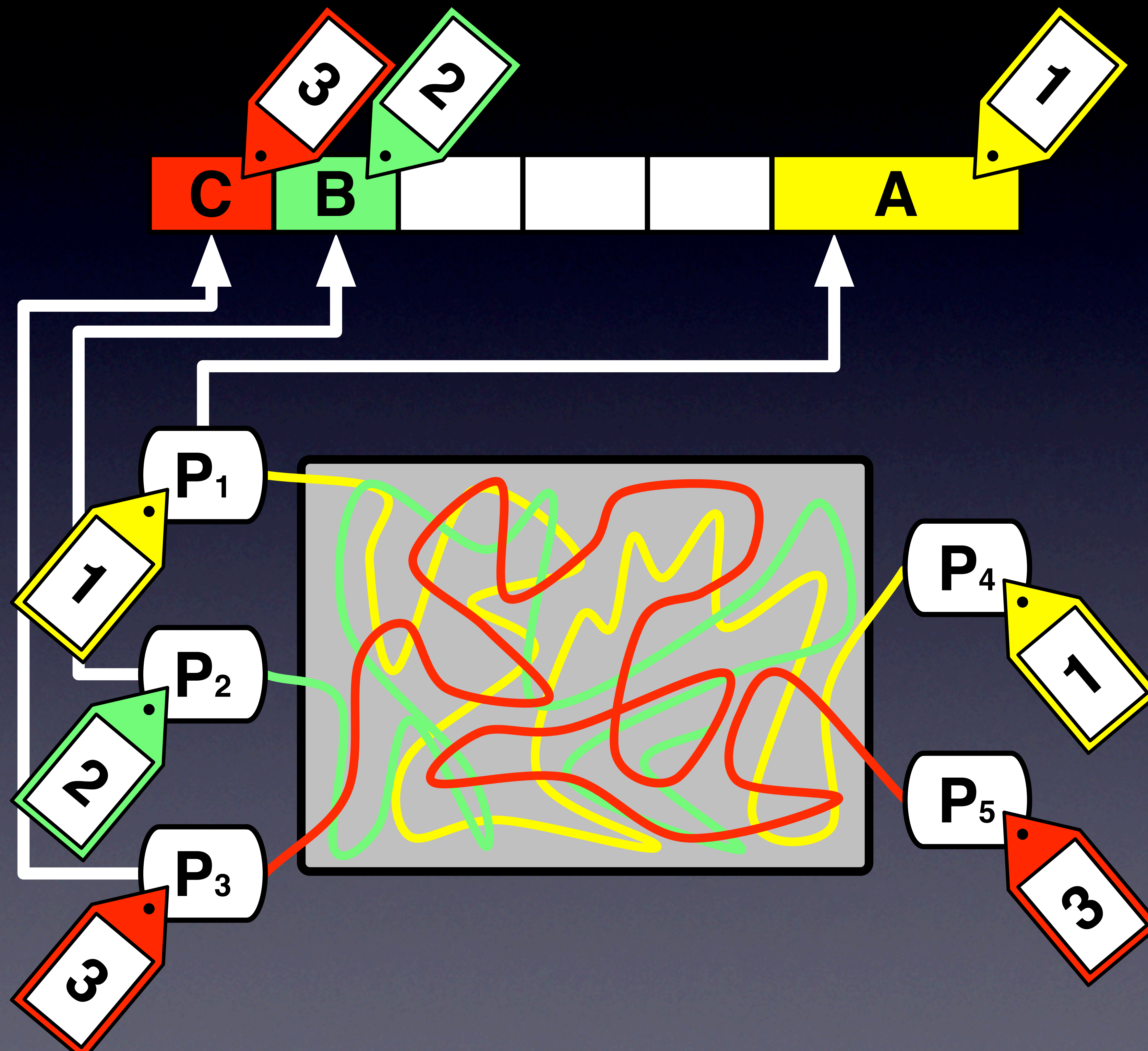

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2. Propagate taint marks
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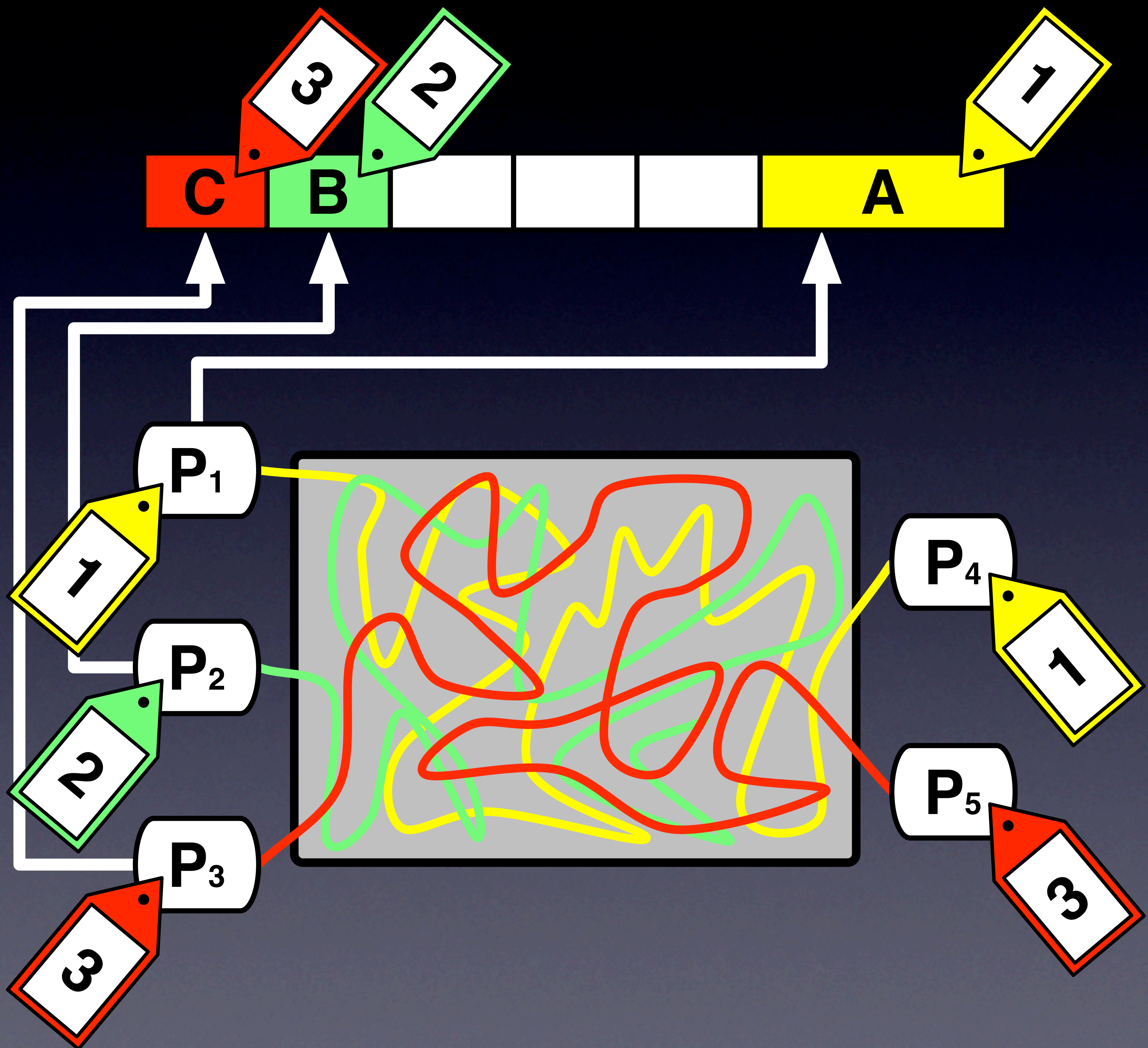

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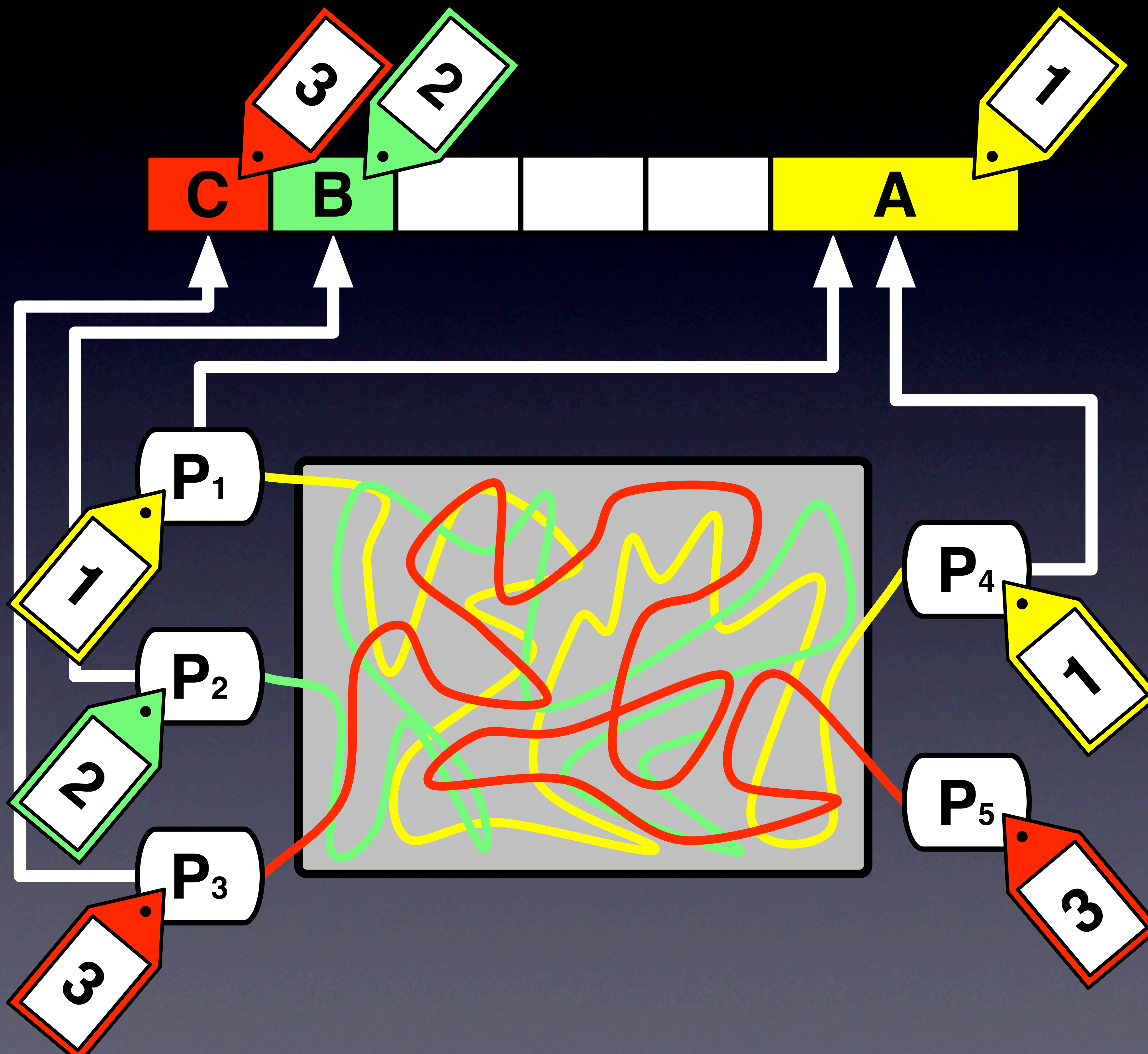

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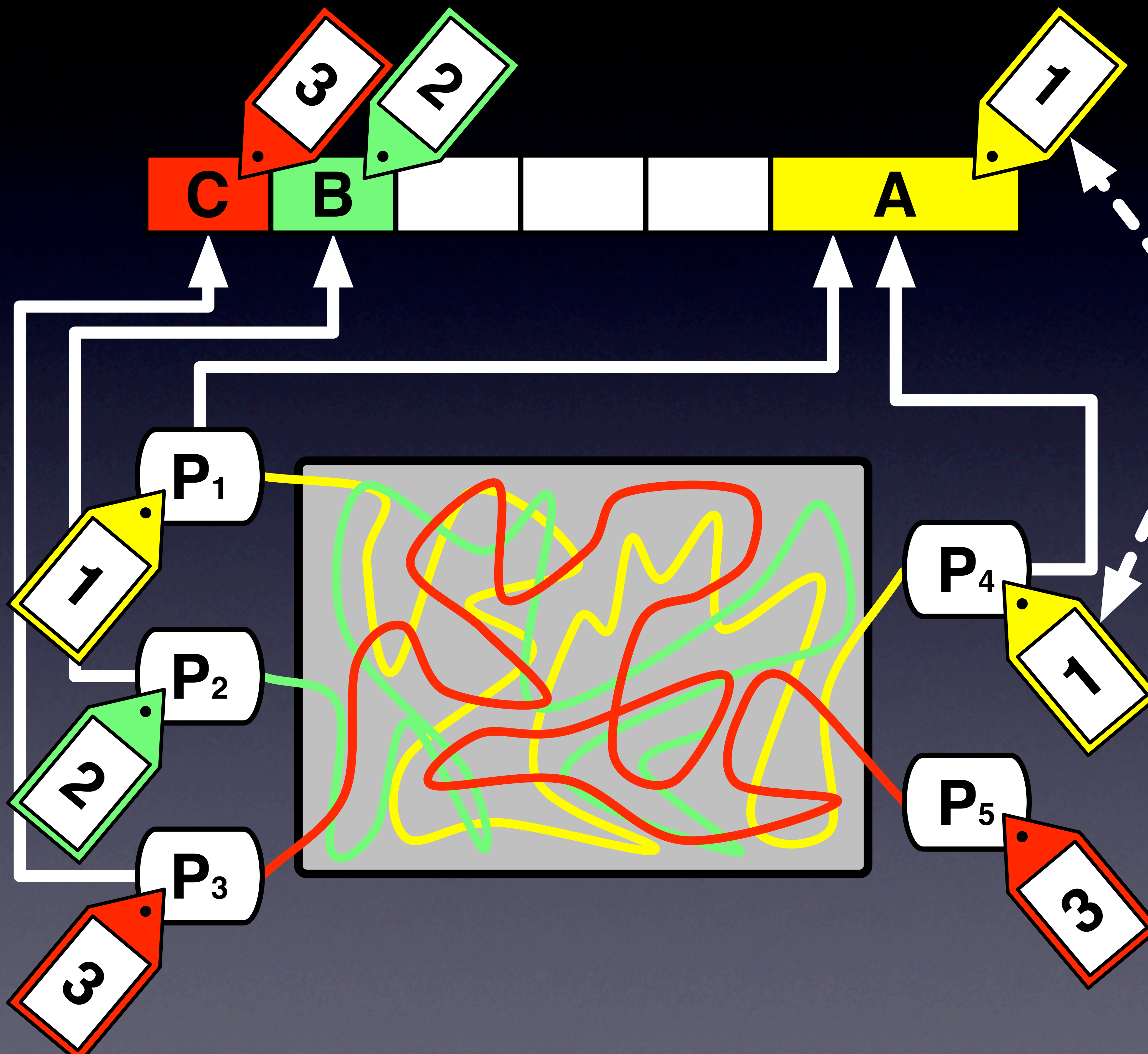

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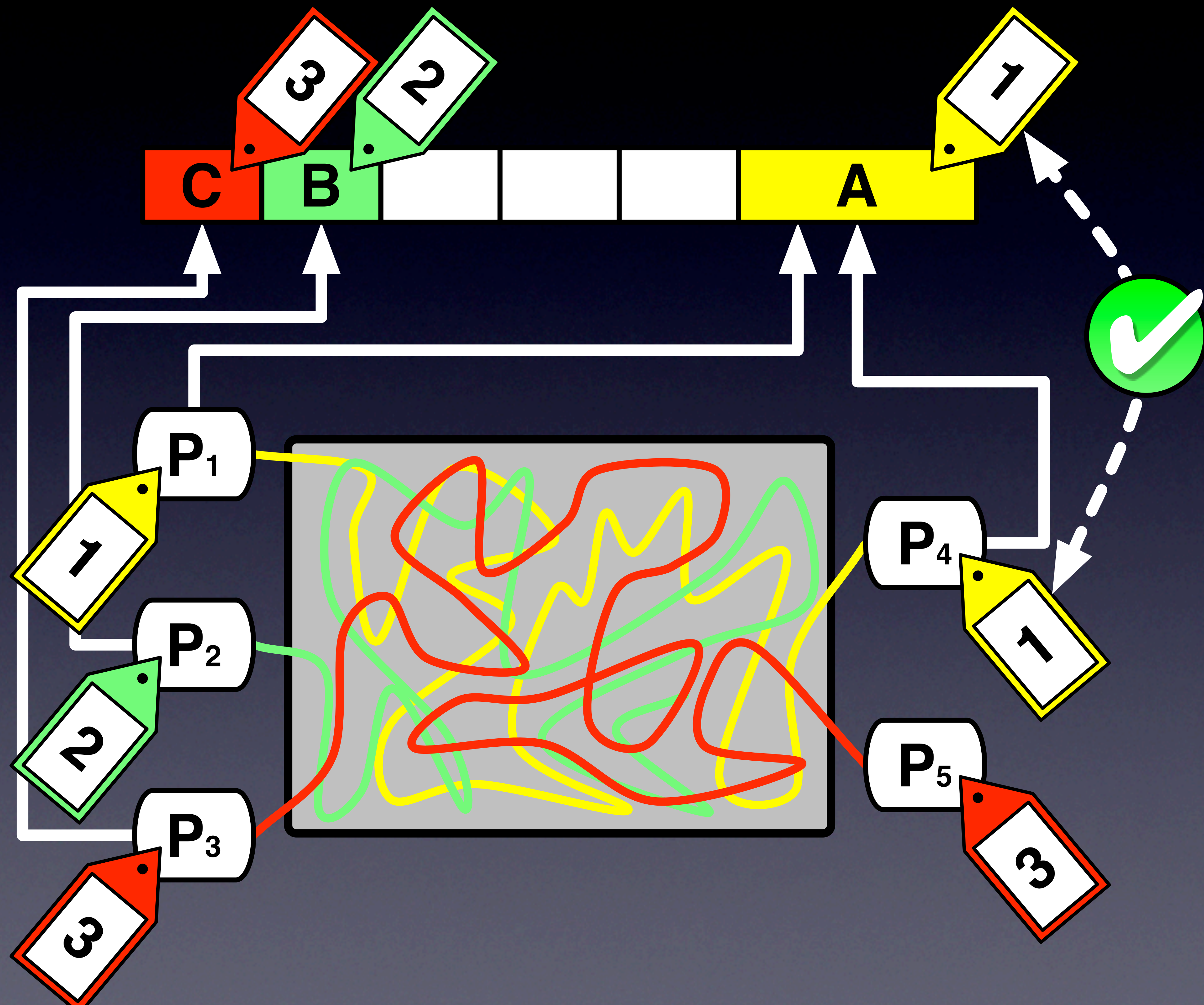

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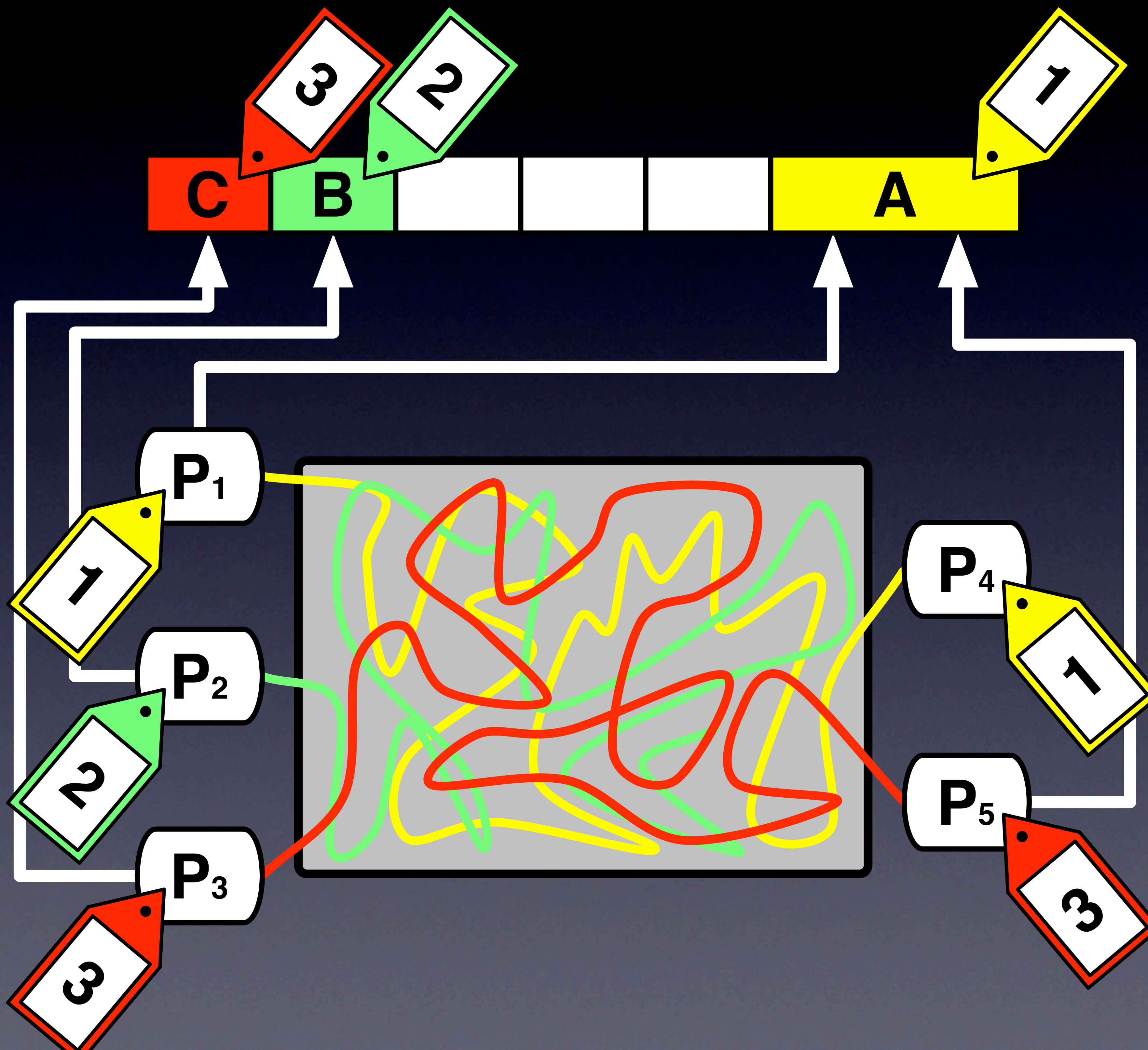

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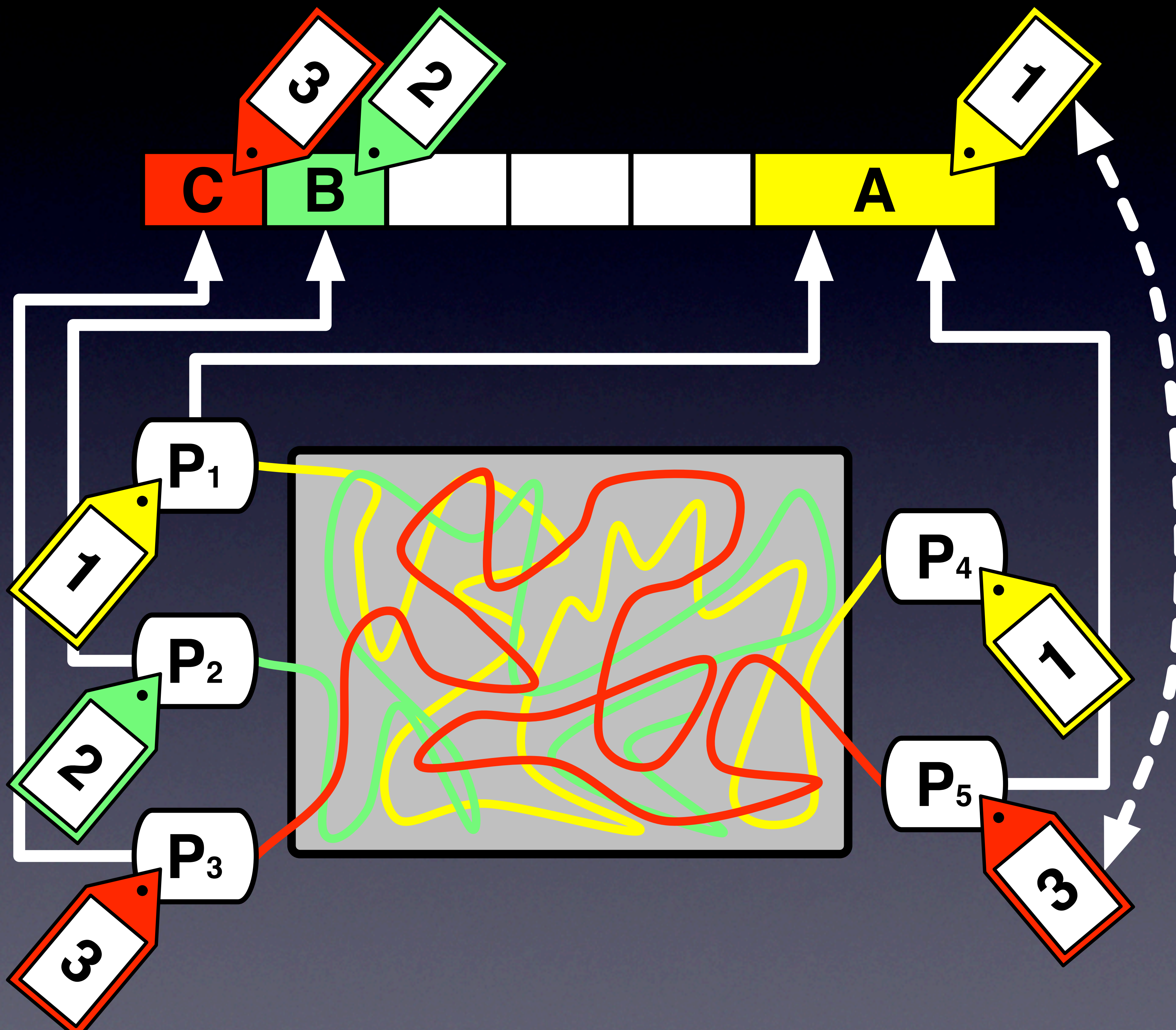

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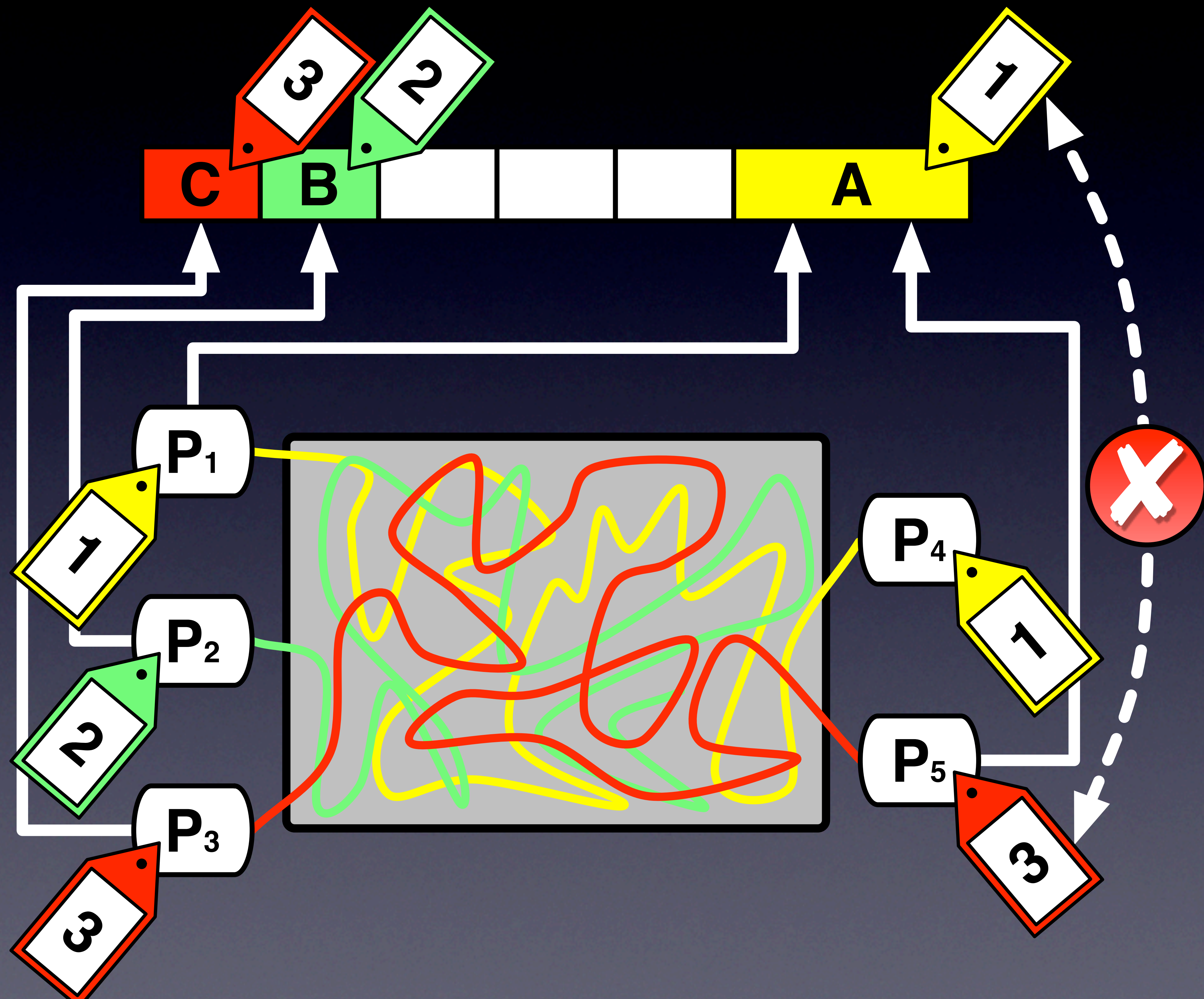
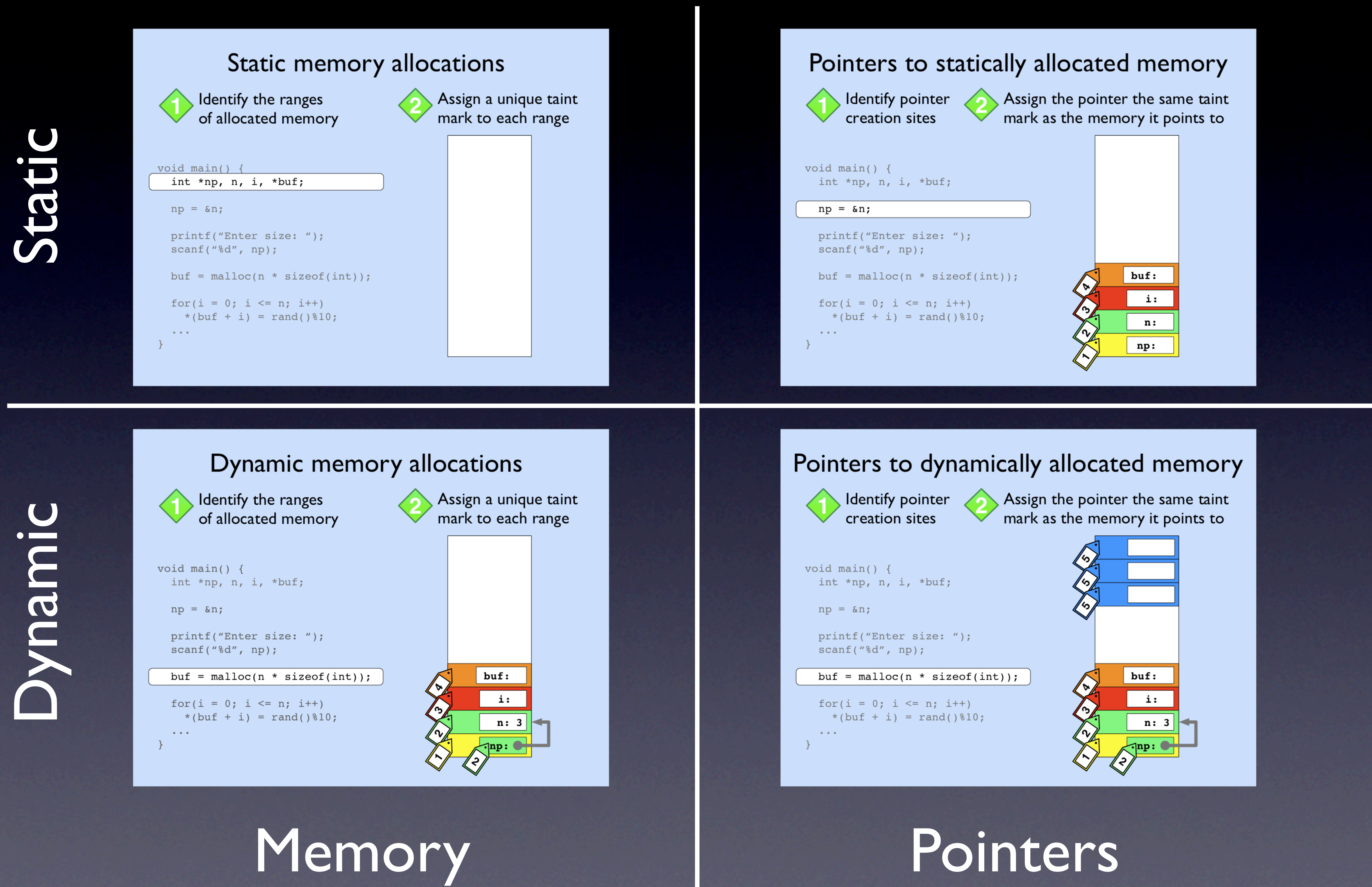


# Outline

- Our approach
    1. Assigning taint marks
    2. Propagating taint marks
    3. Checking taint marks
- Empirical evaluation
- Conclusions

# 1 Assigning taint marks



# Static memory allocations

1 Identify the ranges of allocated memory

2 Assign a unique taint mark to each range

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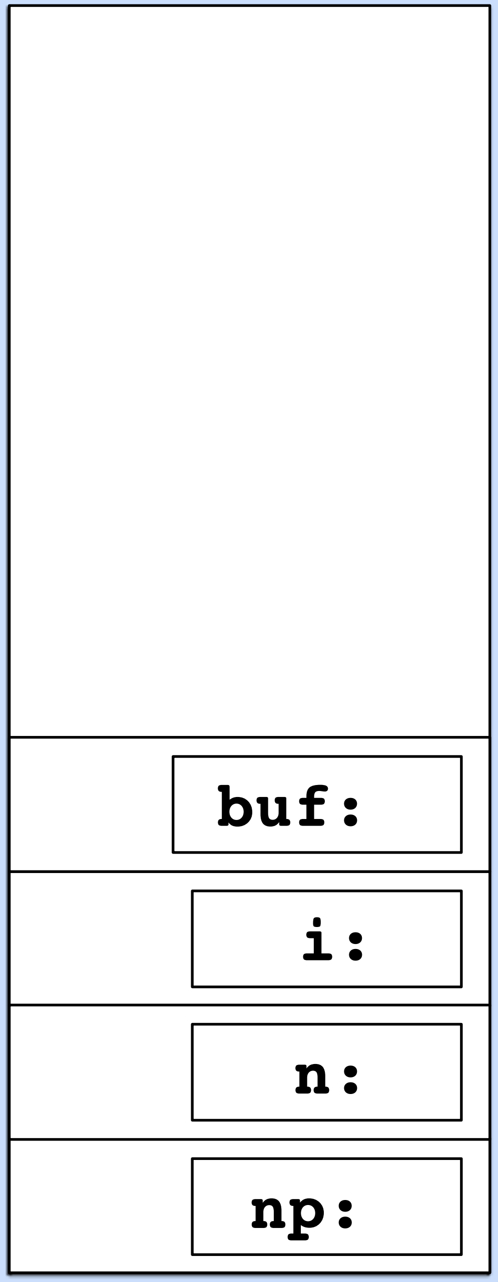

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[&np, &np + sizeof(int *))
```

```
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   np = &n;

   printf("Enter size: ");
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   buf = malloc(n * sizeof(int));

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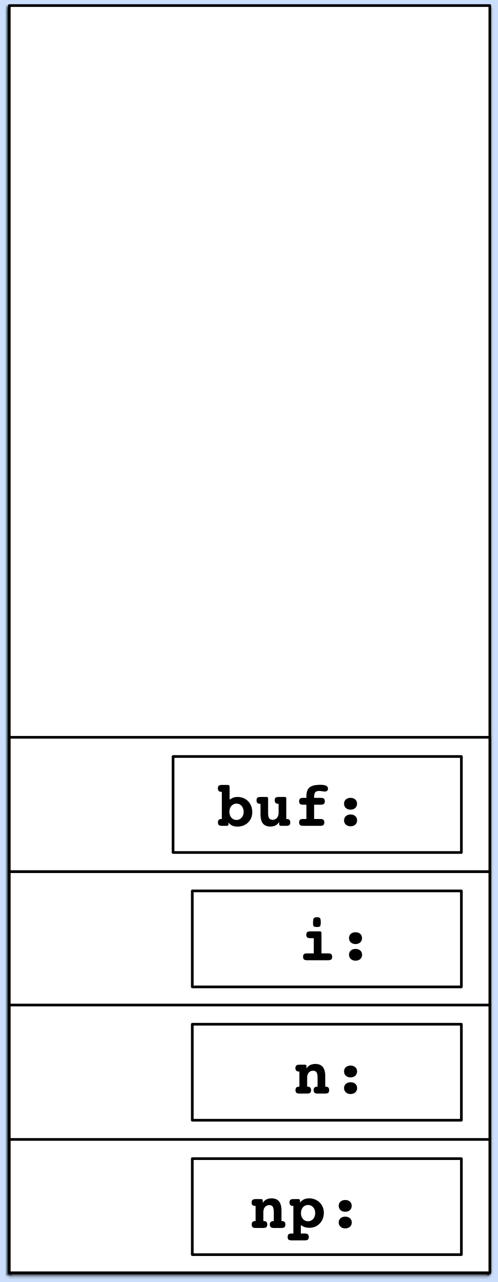

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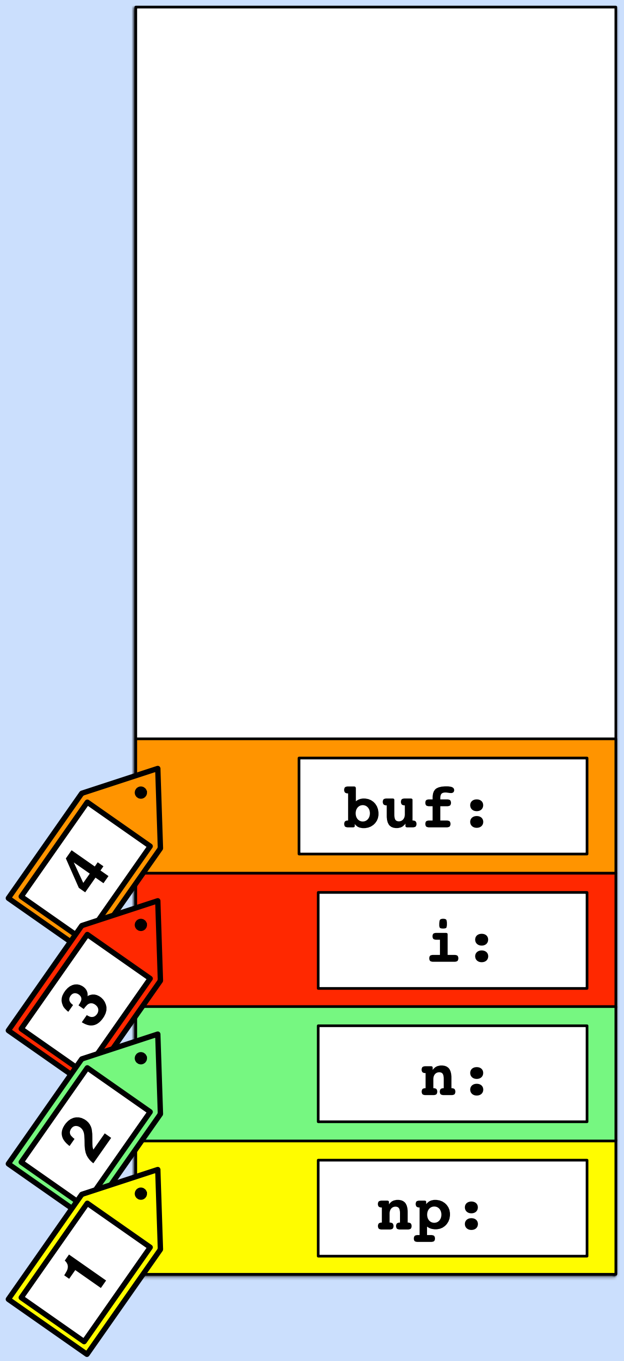

# 1 Assigning taint marks

Static

Dynamic

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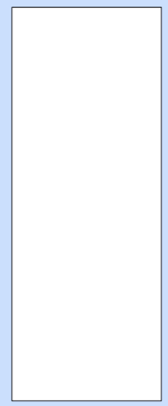

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1. Identify pointer creation sites
2. Assign the pointer the same taint mark as the memory it points to

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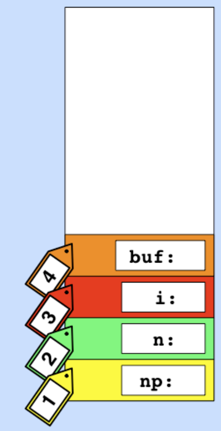


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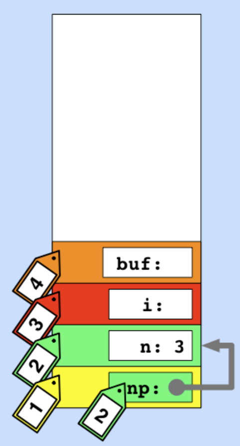


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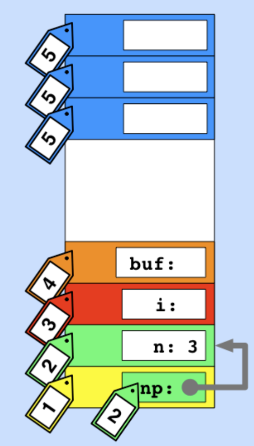



Memory

Pointers

# Pointers to statically allocated memory

1. Identify pointer creation sites
2. Assign the pointer the same taint mark as the memory it points to

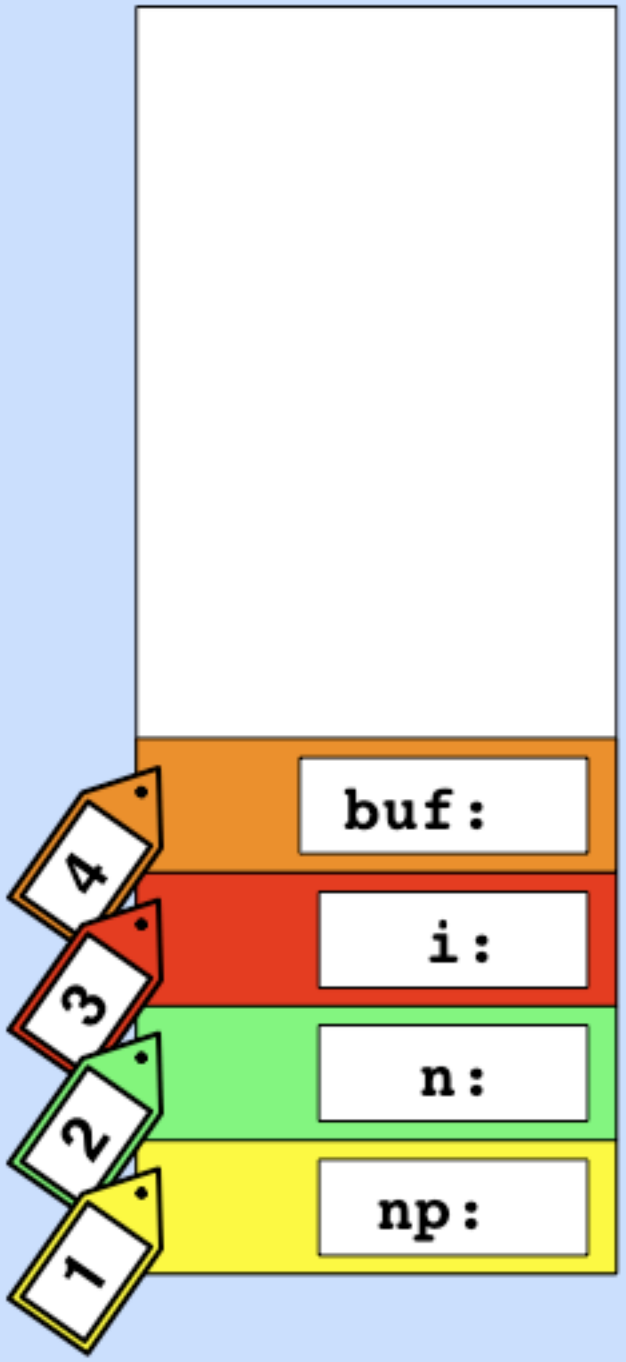
```
void main() {
  int *np, n, i, *buf;

  np = &n;

  printf("Enter size: ");
  scanf("%d", np);

  buf = malloc(n * sizeof(int));

  for(i = 0; i <= n; i++)
    *(buf + i) = rand()%10;
  ...
}
```



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  for(i = 0; i <= n; i++)
    *(buf + i) = rand()%10;
  ...
}
```
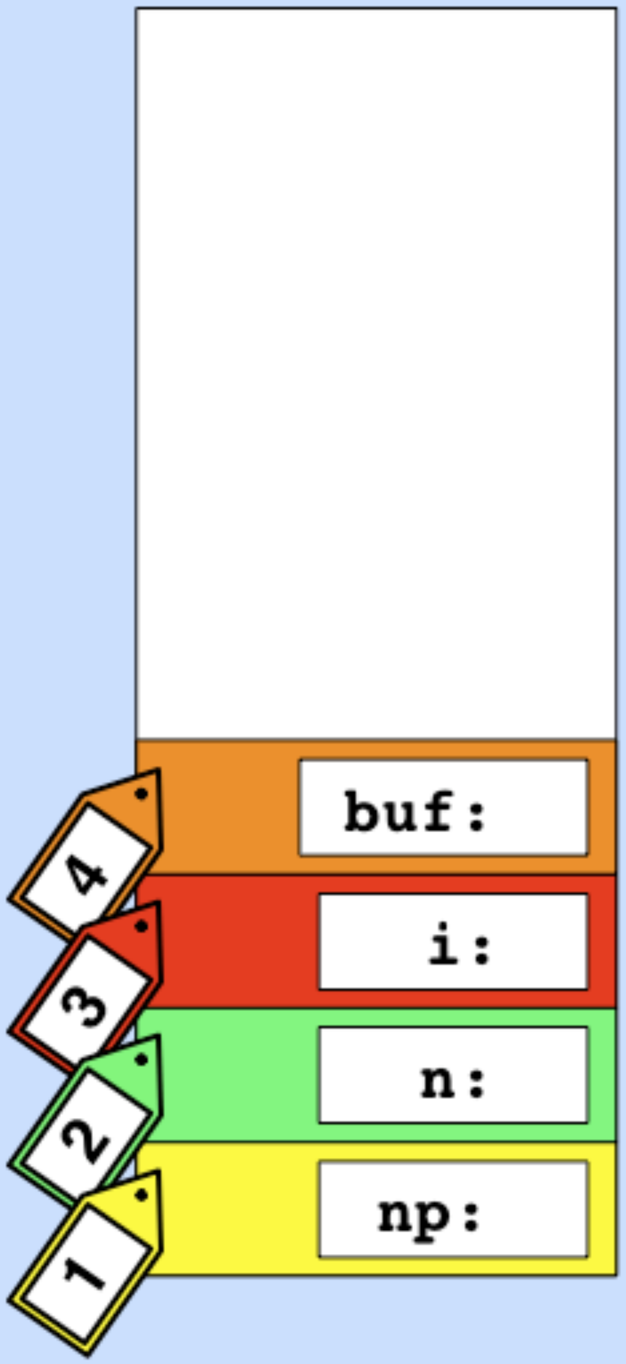

address-of operator (& )



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  buf = malloc(n * sizeof(int));

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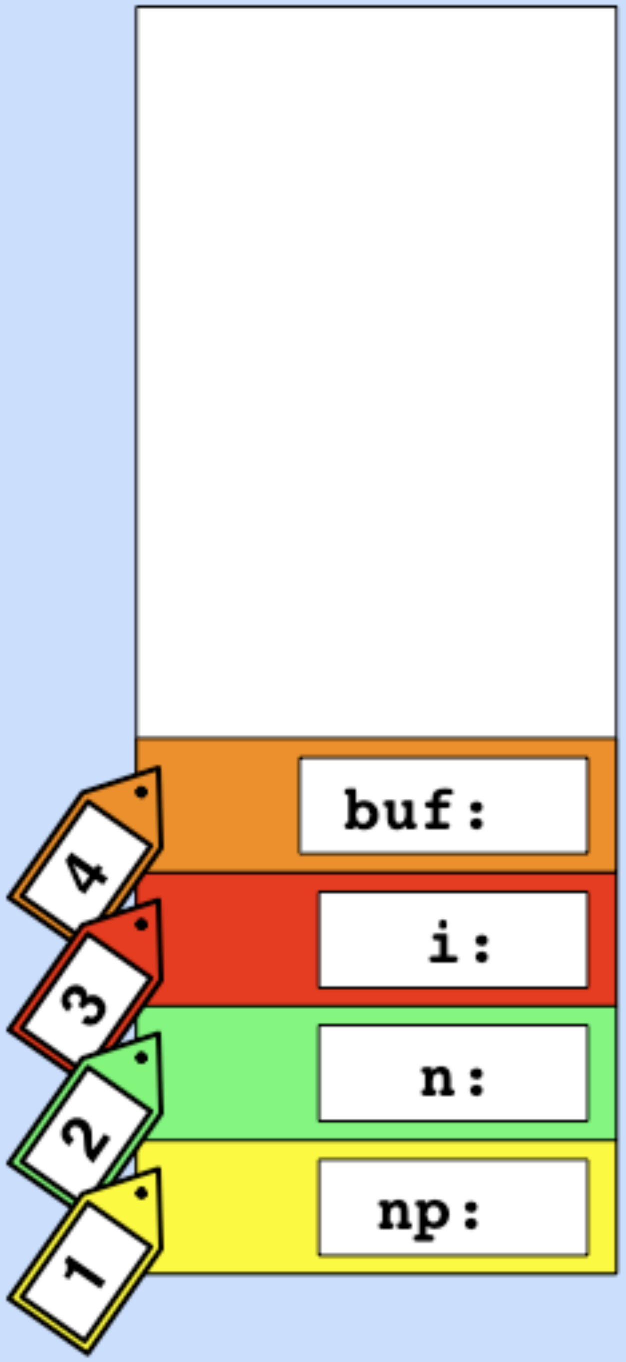
  ...
}
```



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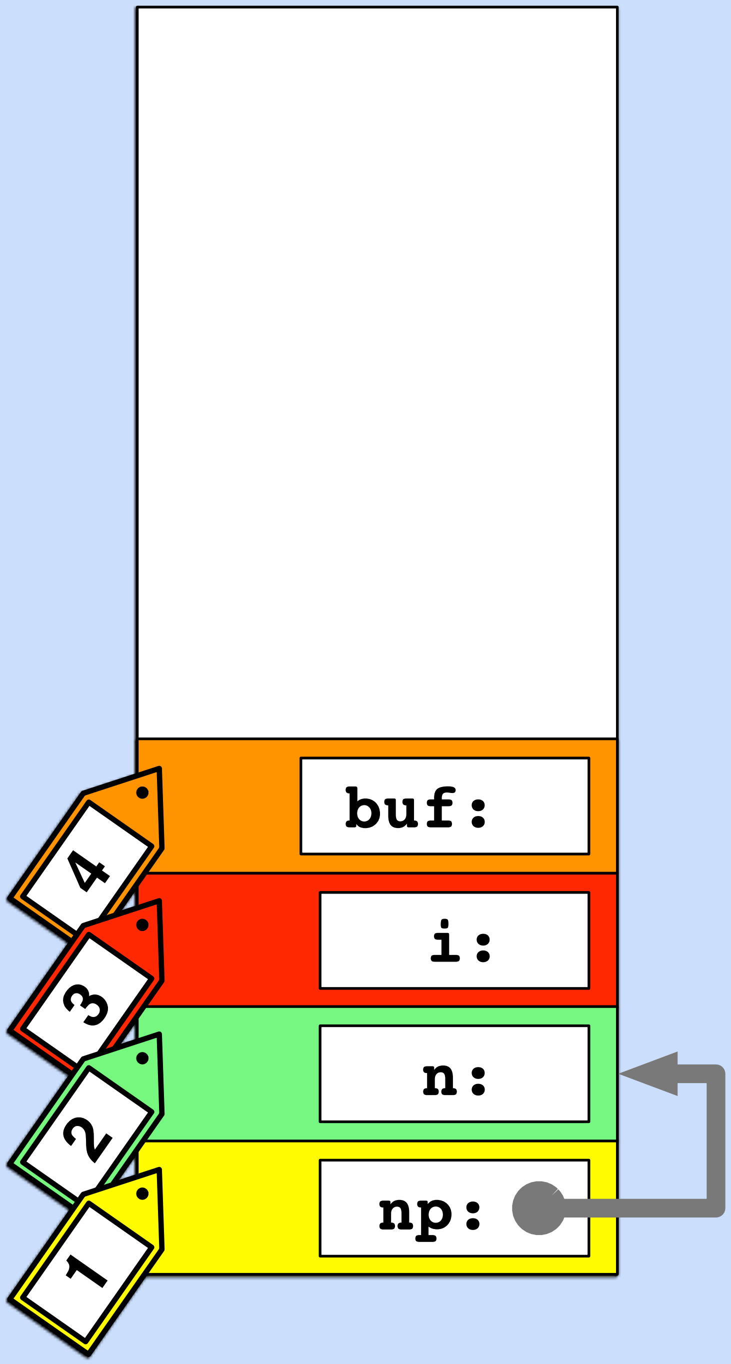

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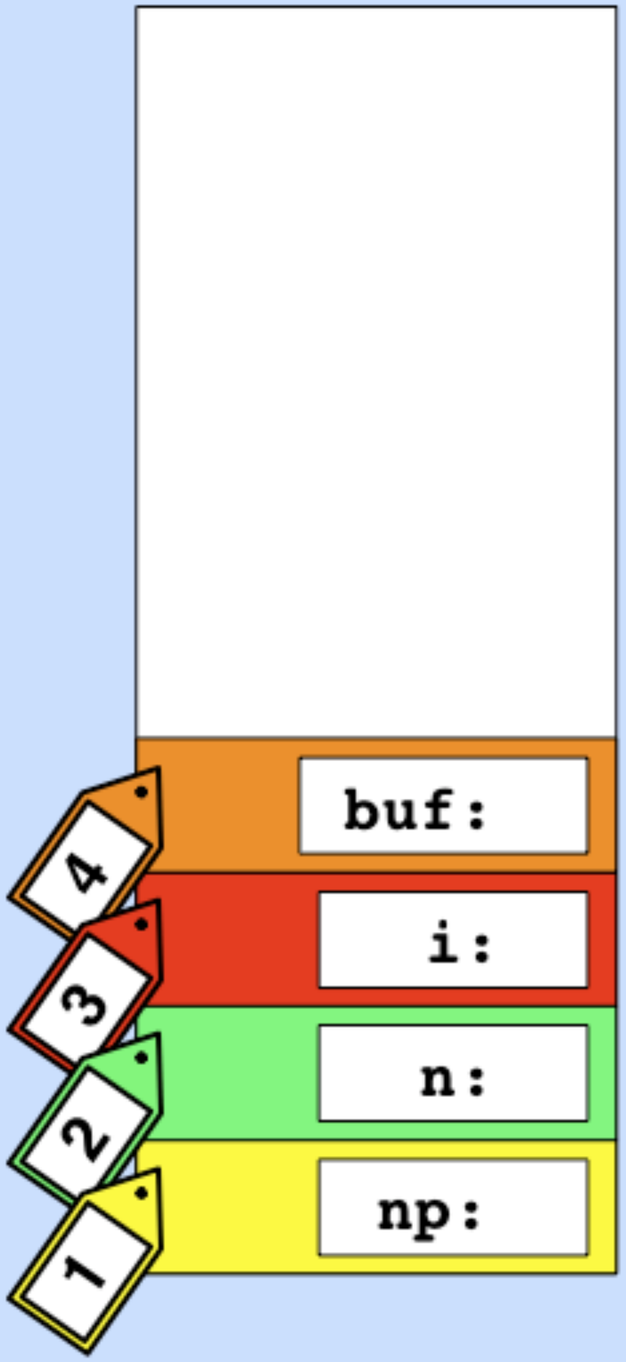

# 1 Assigning taint marks

Static

## Static memory allocations

1. Identify the ranges of allocated memory
2. Assign a unique taint mark to each range

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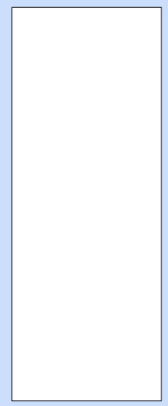

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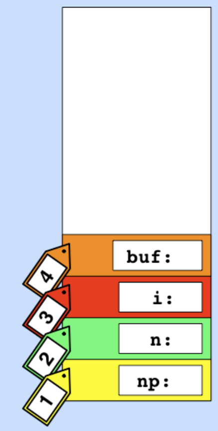


Dynamic

## Dynamic memory allocations

1. Identify the ranges of allocated memory
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```
void main() {
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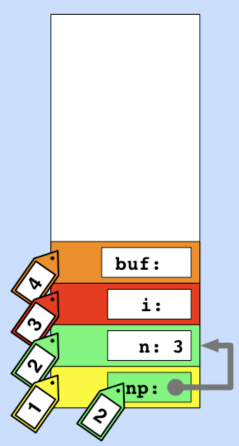


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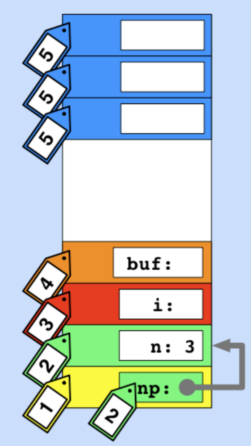
```




Memory

Pointers

# Dynamic memory allocations

1. Identify the ranges of allocated memory

2. Assign a unique taint mark to each range

```
void main() {
  int *np, n, i, *buf;

  np = &n;

  printf("Enter size: ");
  scanf("%d", np);

  buf = malloc(n * sizeof(int));

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    *(buf + i) = rand()%10;
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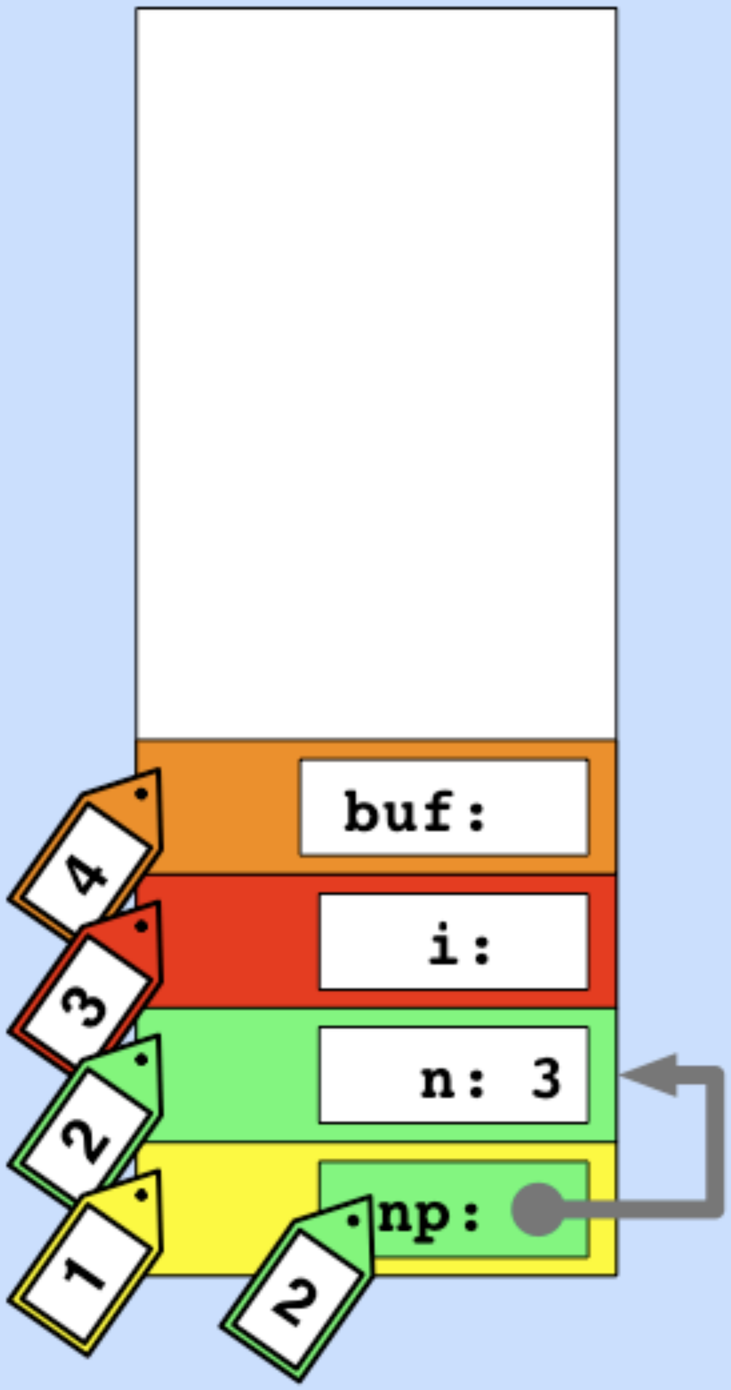
}
```



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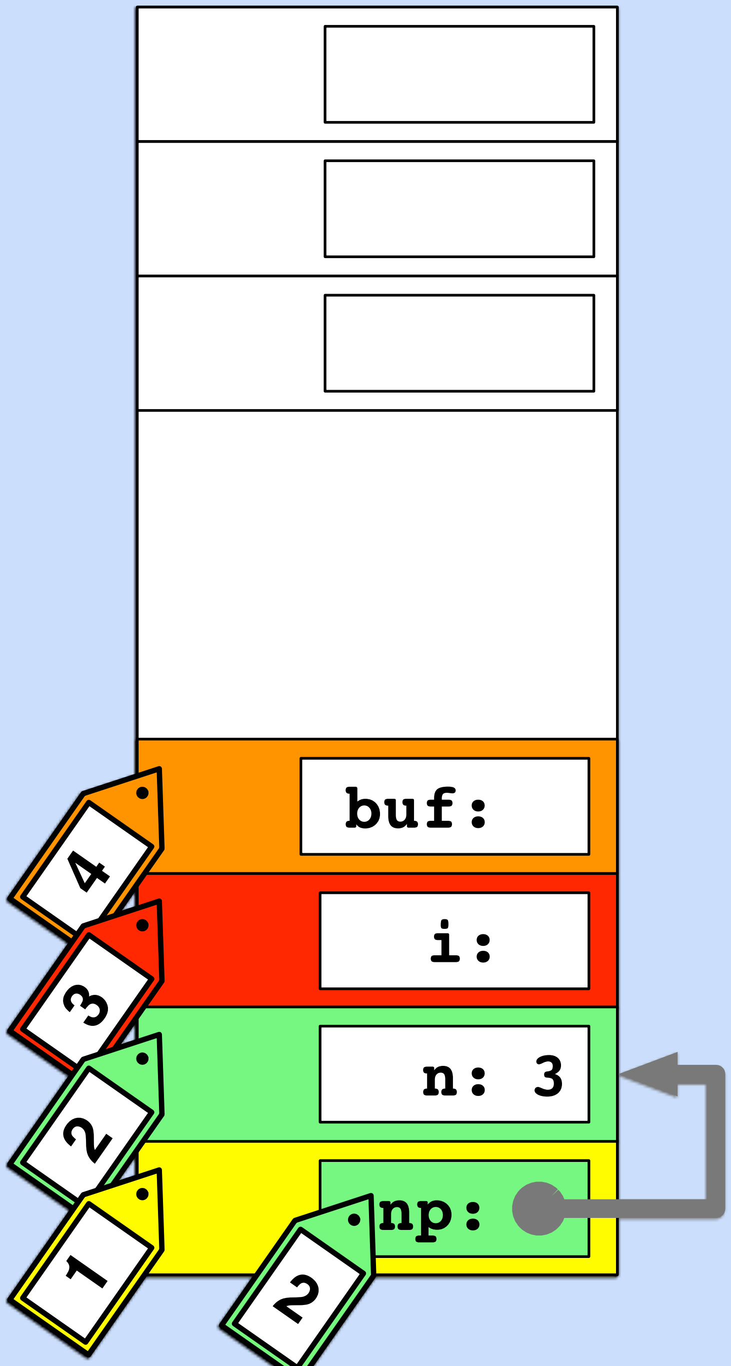

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```
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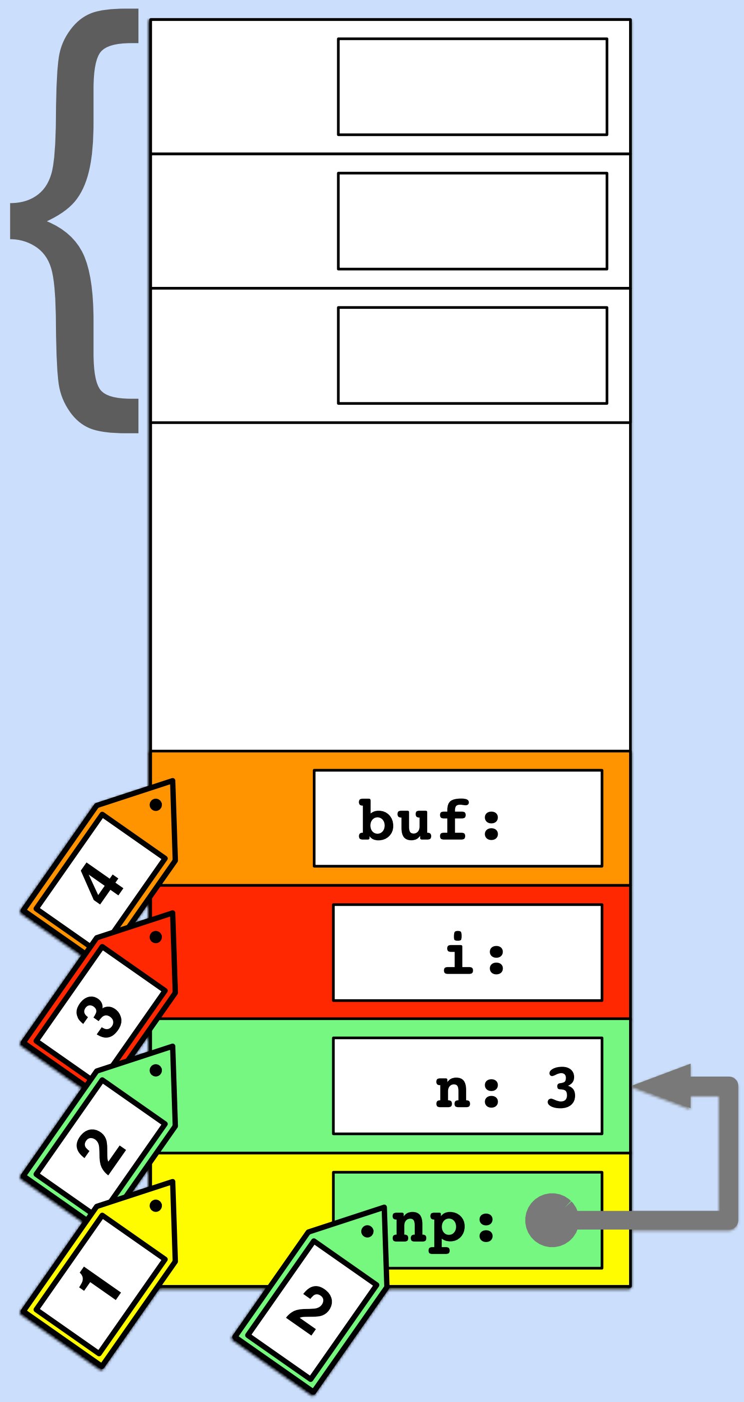
  np = &n;

  printf("Enter size: ");
  scanf(
  buf = malloc(n * sizeof(int));

  for(i = 0; i <= n; i++)
    *(buf + i) = rand()%10;
  ...
}
```

[ret, ret + arg0)



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  for(i = 0; i <= n; i++)
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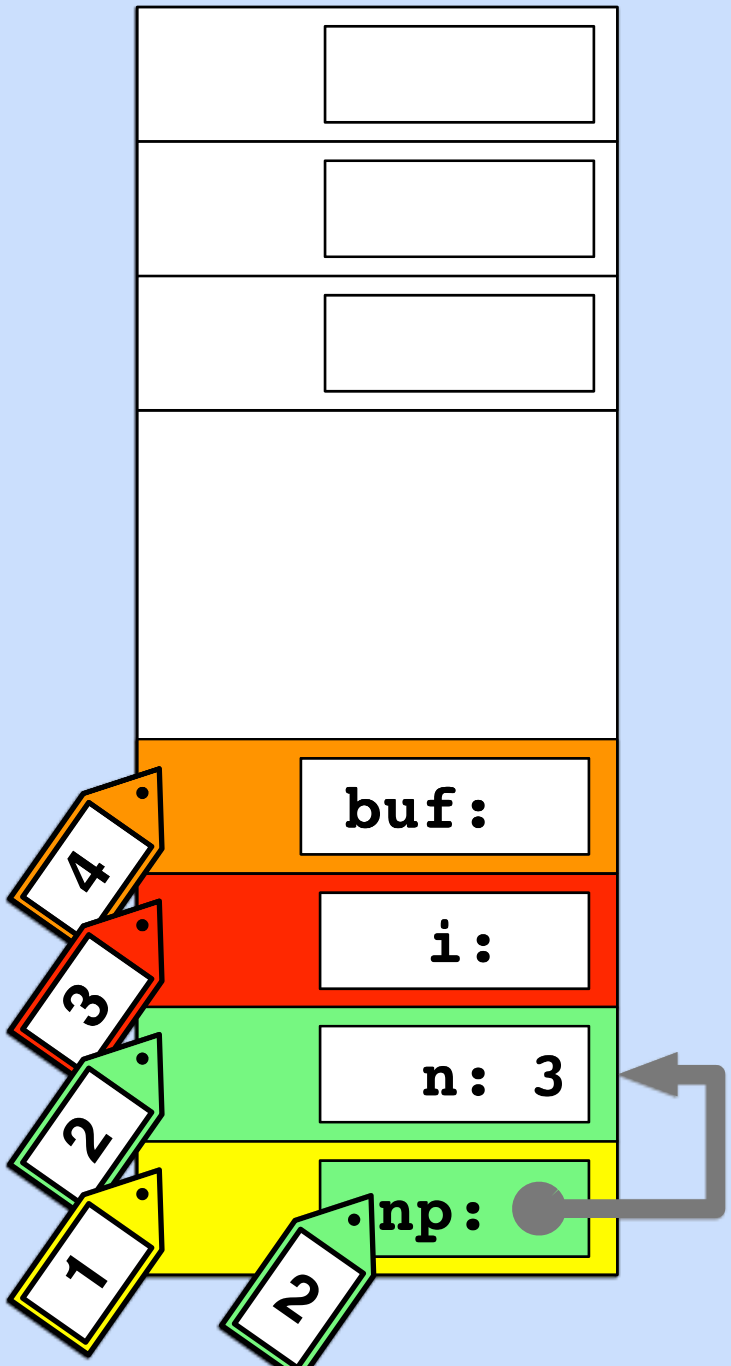

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  printf(“Enter size: “);
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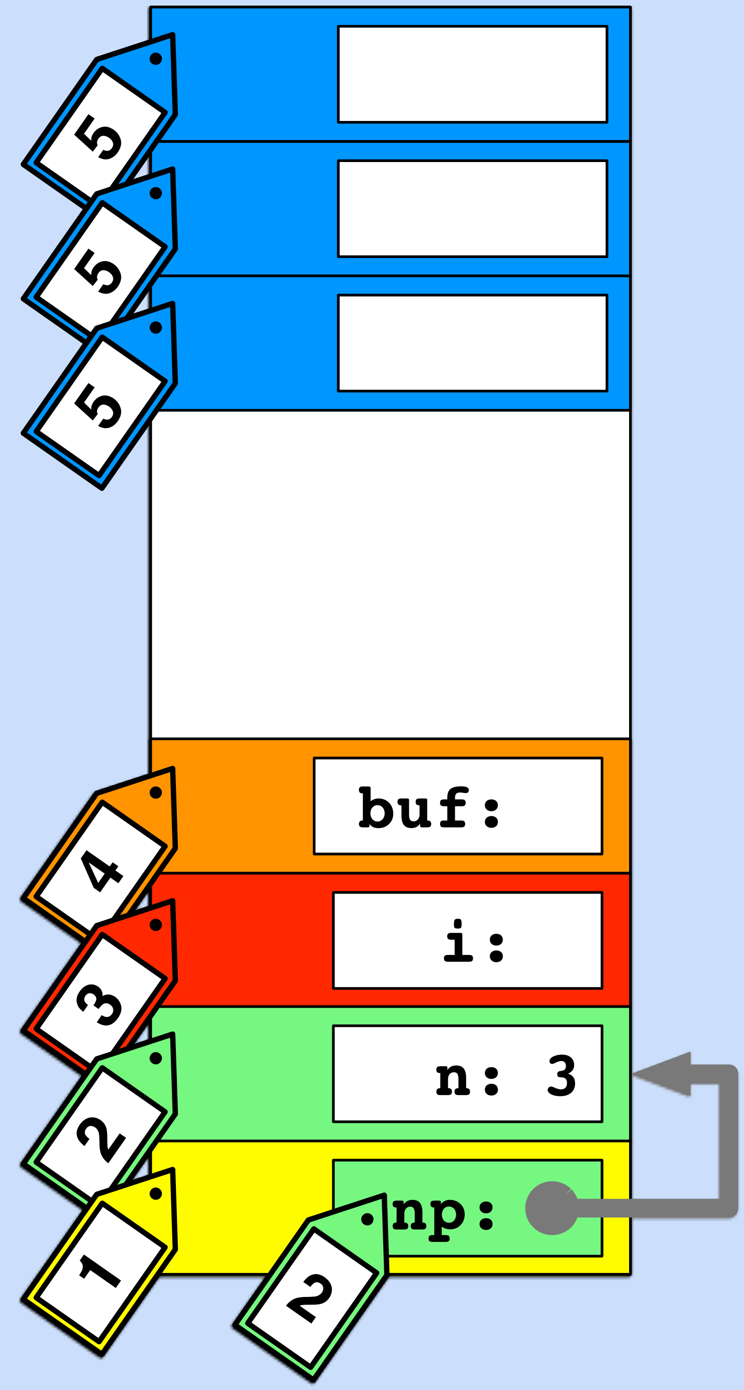

# 1 Assigning taint marks

Static

## Static memory allocations

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  printf("Enter size: ");
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  for(i = 0; i <= n; i++)
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```

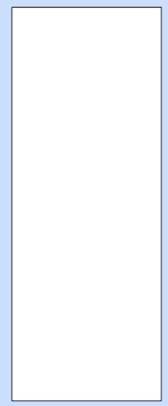

## Pointers to statically allocated memory

1. Identify pointer creation sites
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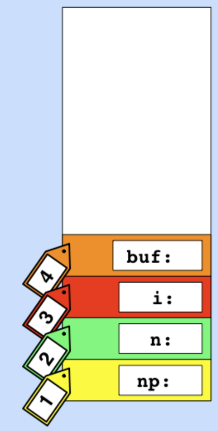


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  for(i = 0; i <= n; i++)
    *(buf + i) = rand()%10;
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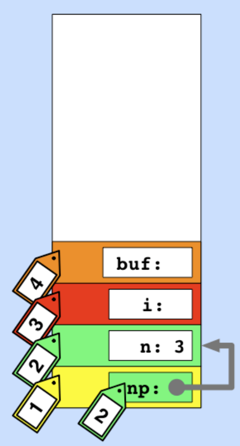


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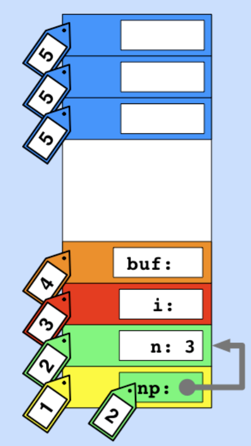


Memory

Pointers

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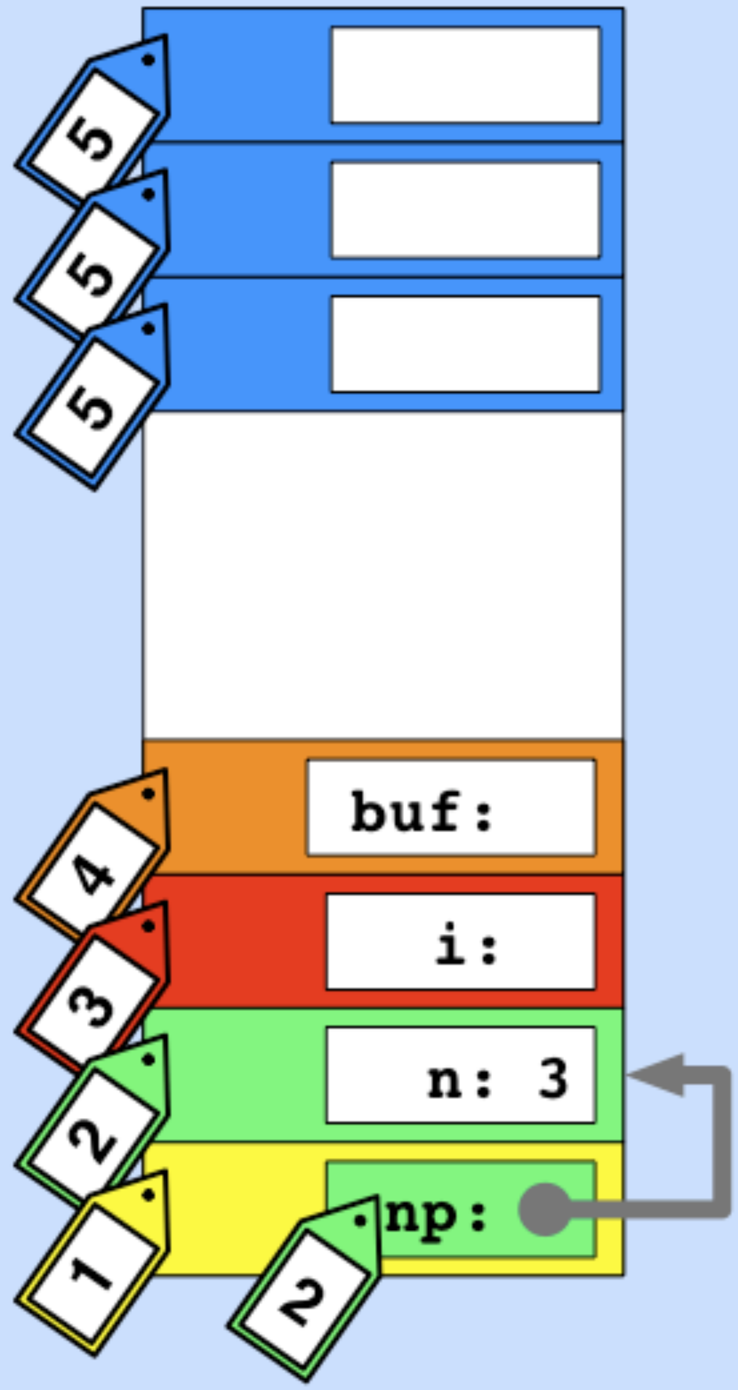

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  printf("Enter size: ");
  scanf(

  buf = malloc(n * sizeof(int));

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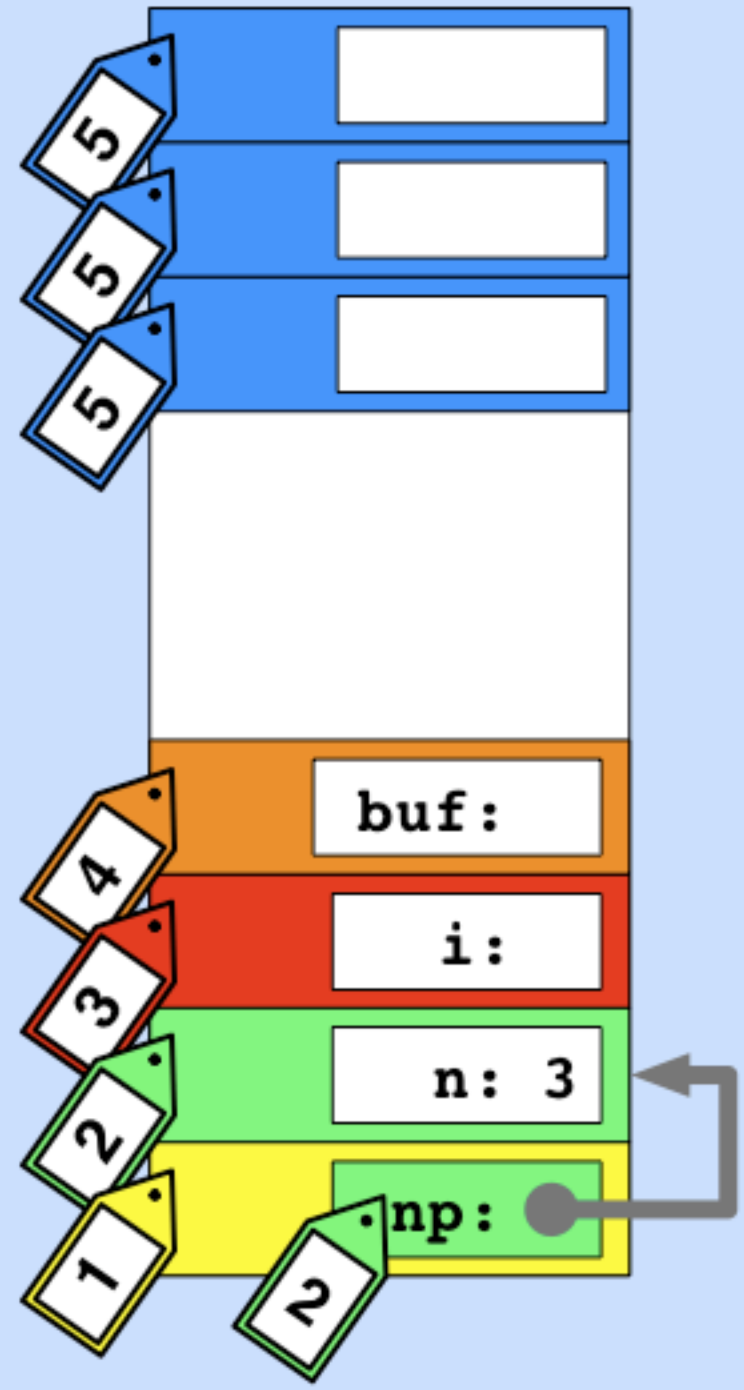
    *(buf + i) = rand()%10;
  ...
}
```

return value of malloc



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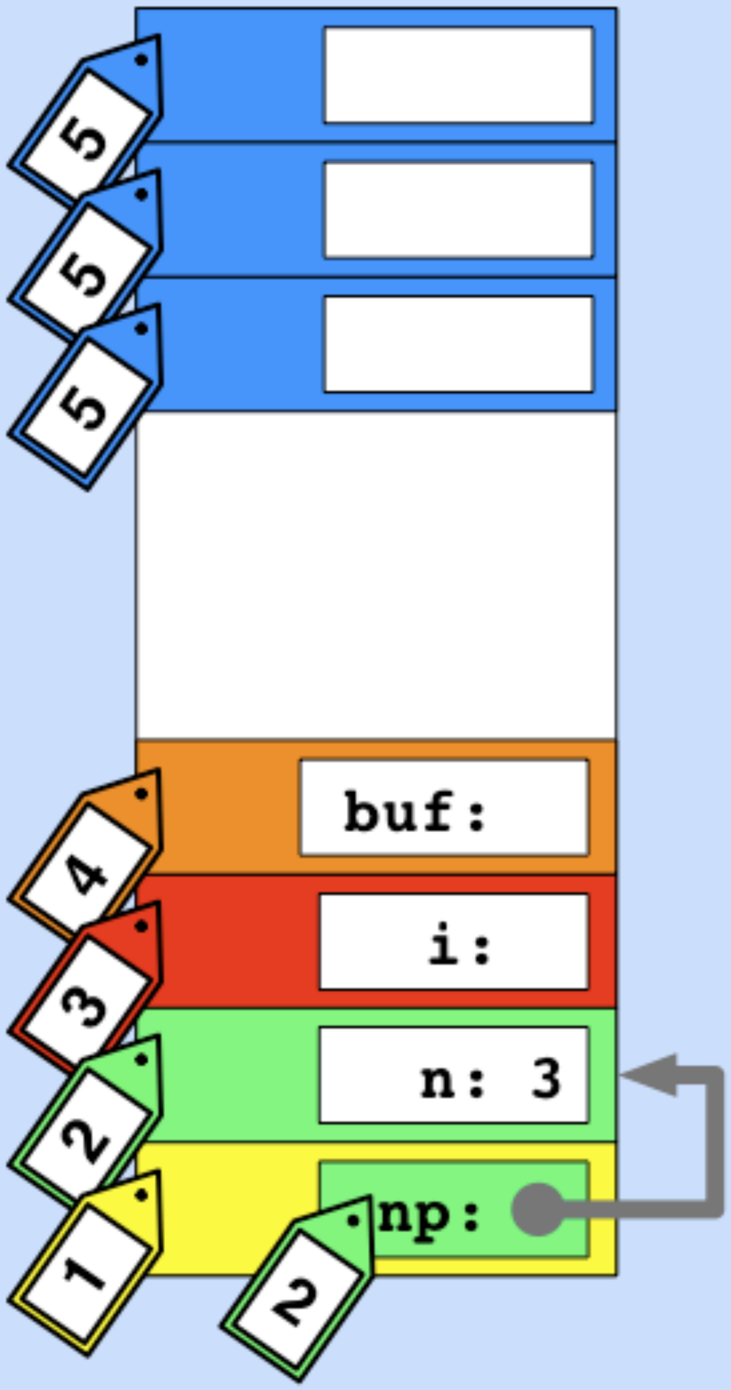

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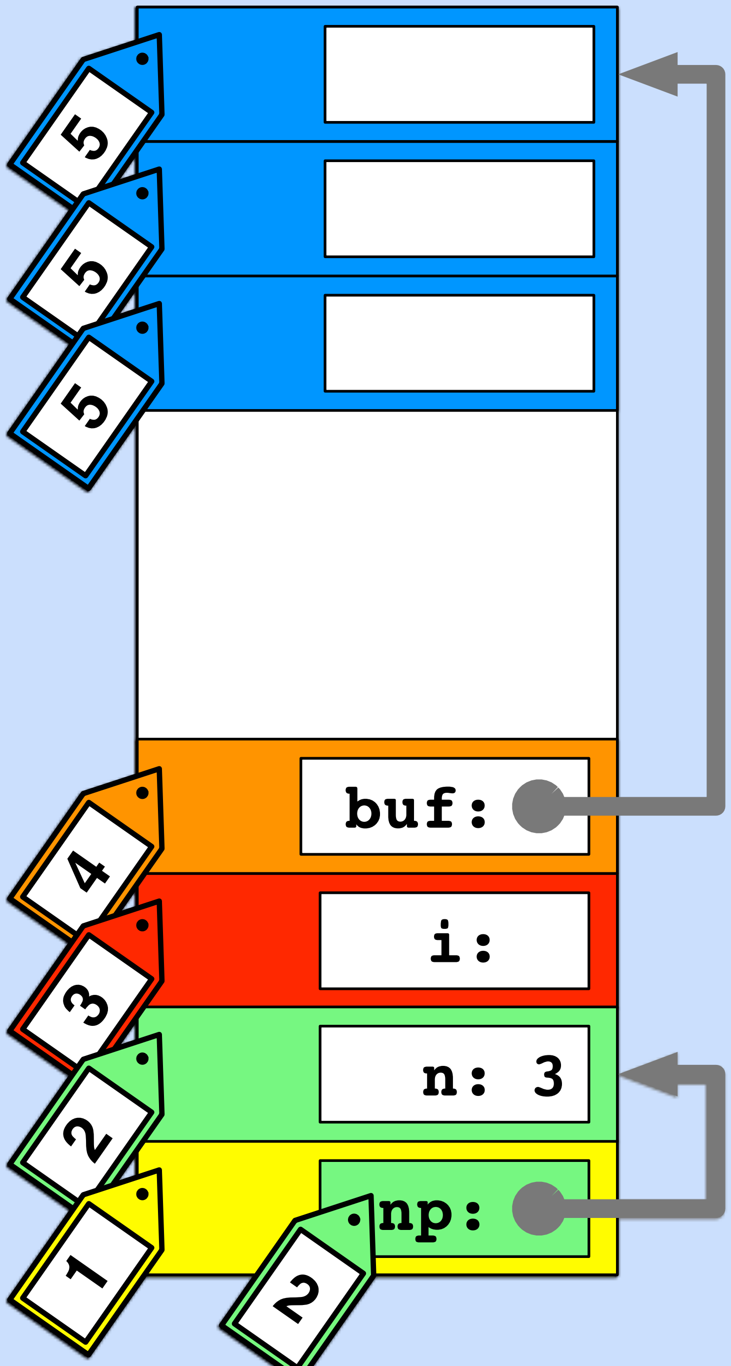

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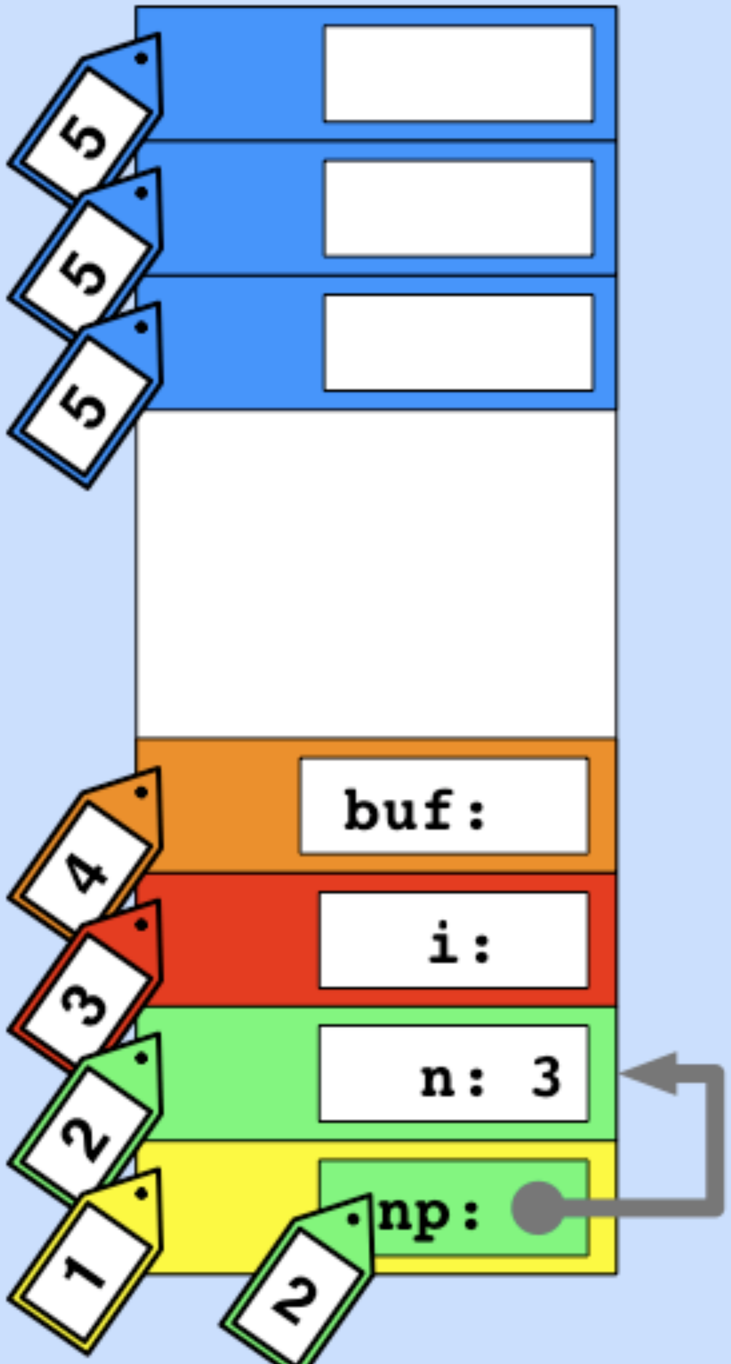

# 1 Assigning taint marks

Static

Dynamic

## Static memory allocations

1. Identify the ranges of allocated memory
2. Assign a unique taint mark to each range

```
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  np = &n;

  printf(“Enter size: “);
  scanf(“%d”, np);

  buf = malloc(n * sizeof(int));

  for(i = 0; i <= n; i++)
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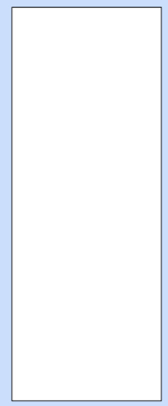

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  for(i = 0; i <= n; i++)
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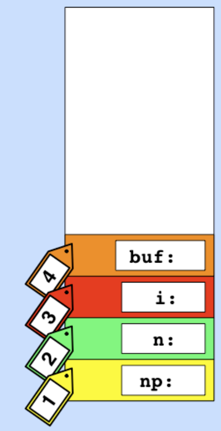


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```
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}
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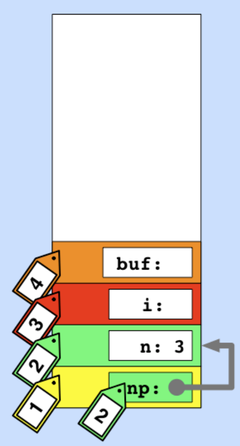


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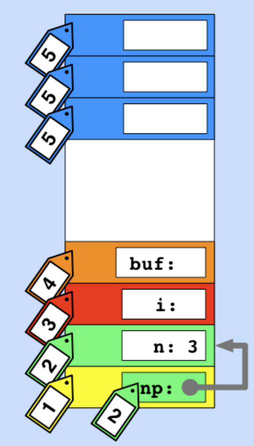



Memory

Pointers

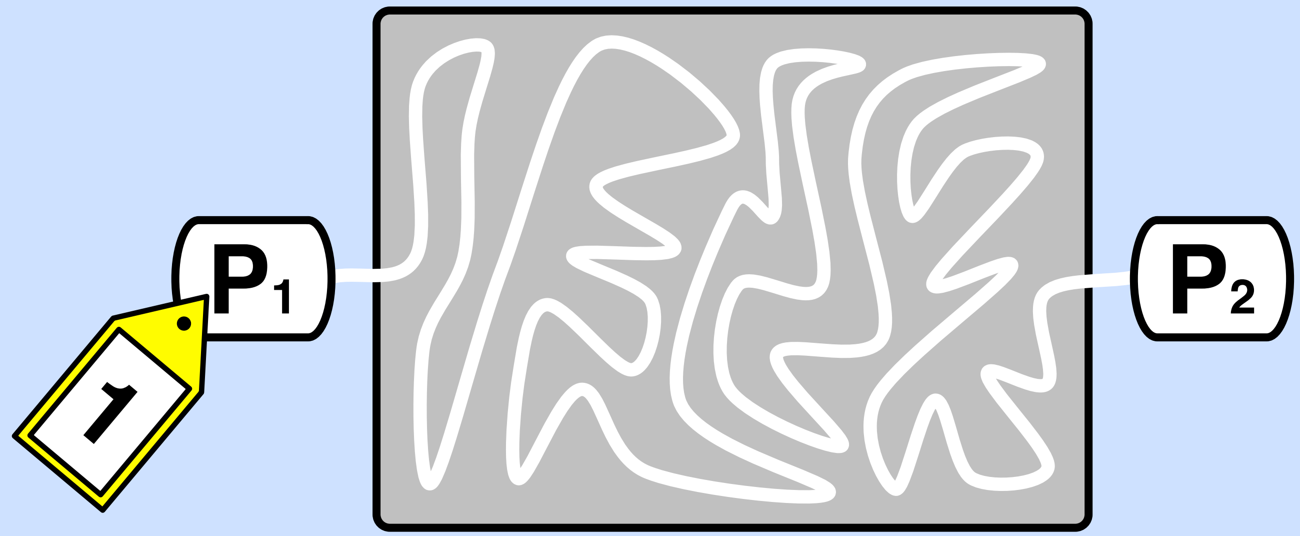
# 2 Propagating taint marks

Overview

Addition, Subtraction

AND

Multiplication, Division,
OR, XOR



# 2 Propagating taint marks

Overview

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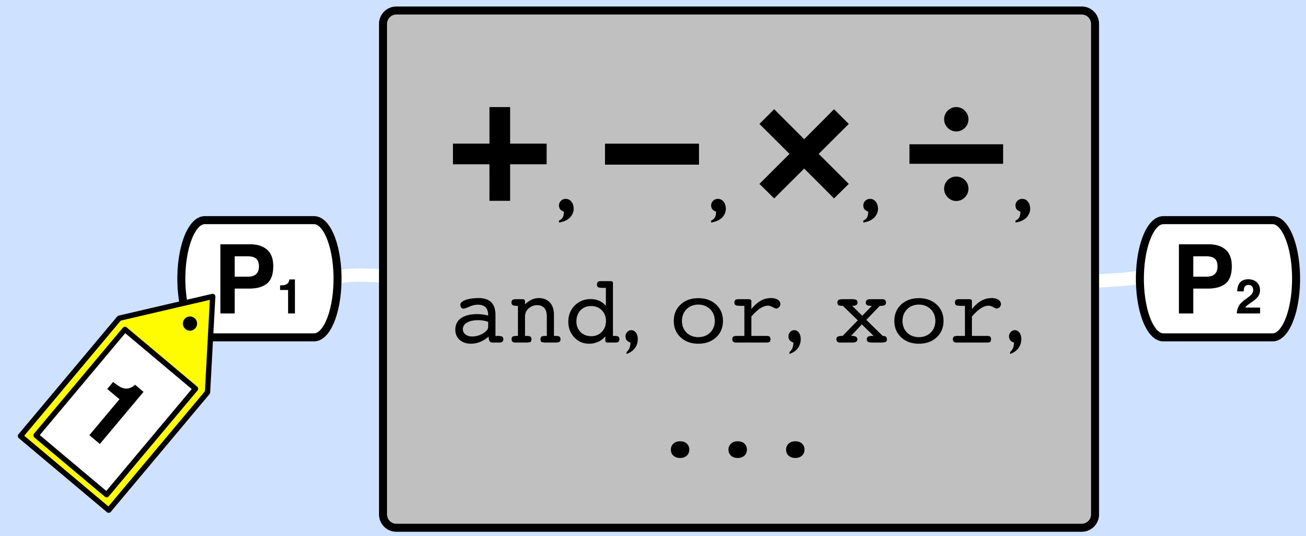

# 2 Propagating taint marks

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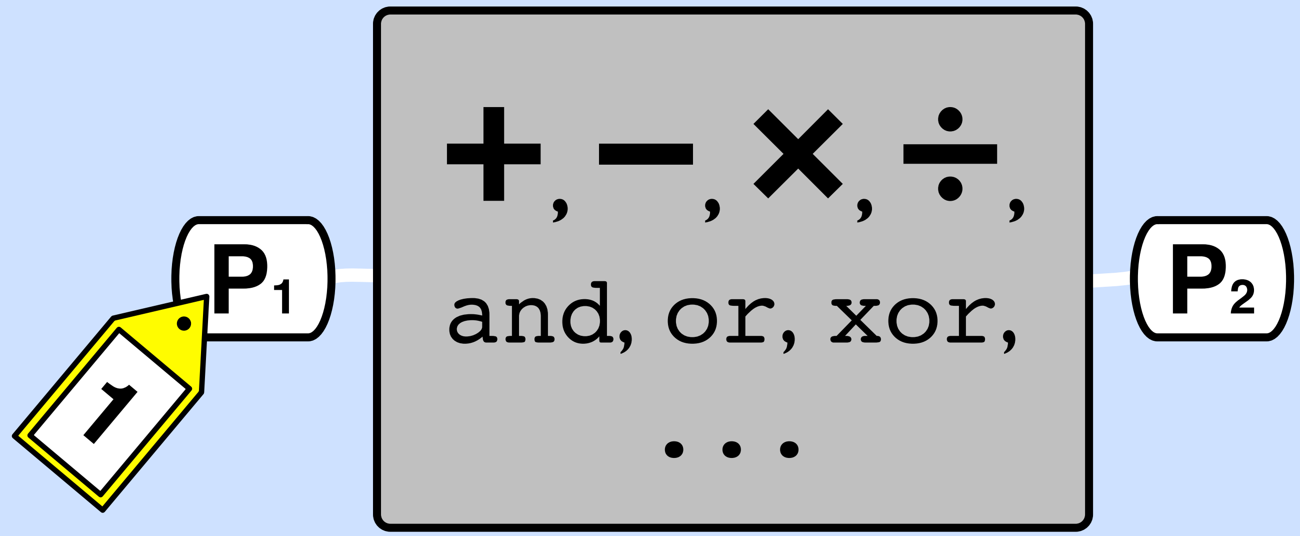


Should the result be tainted?
If so, how?

# 2 Propagating taint marks

Overview

Addition, Subtraction

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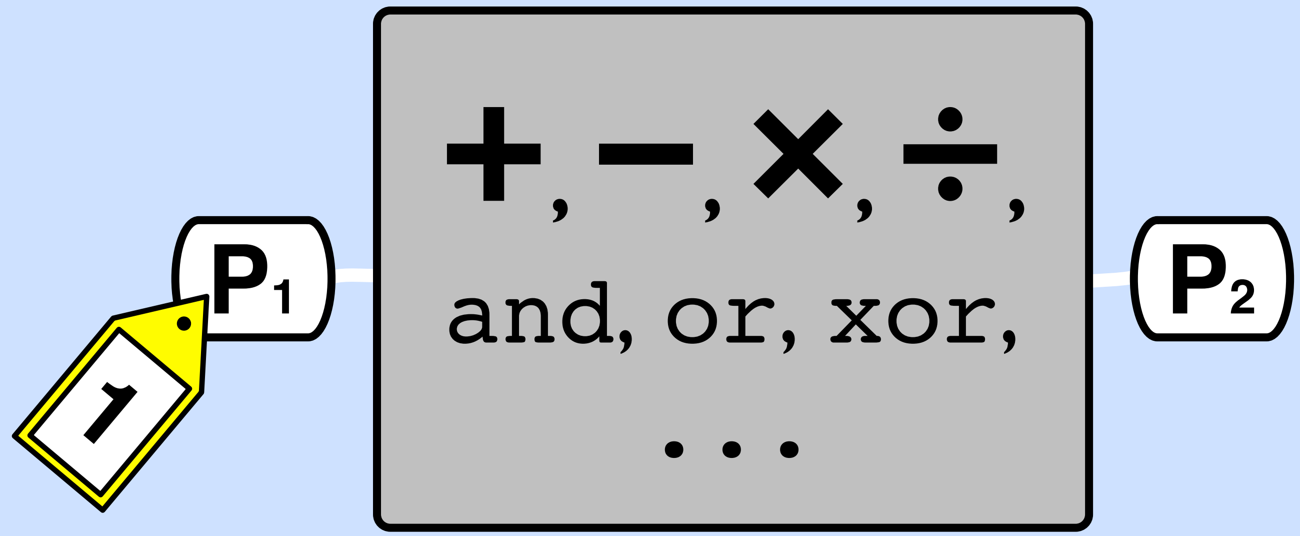
Multiplication, Division, OR, XOR




Should the result be tainted?
If so, how?

- Propagation must take into account both operation semantics and programmer intent

# 2 Propagating taint marks

Overview

Addition, Subtraction

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Multiplication, Division,
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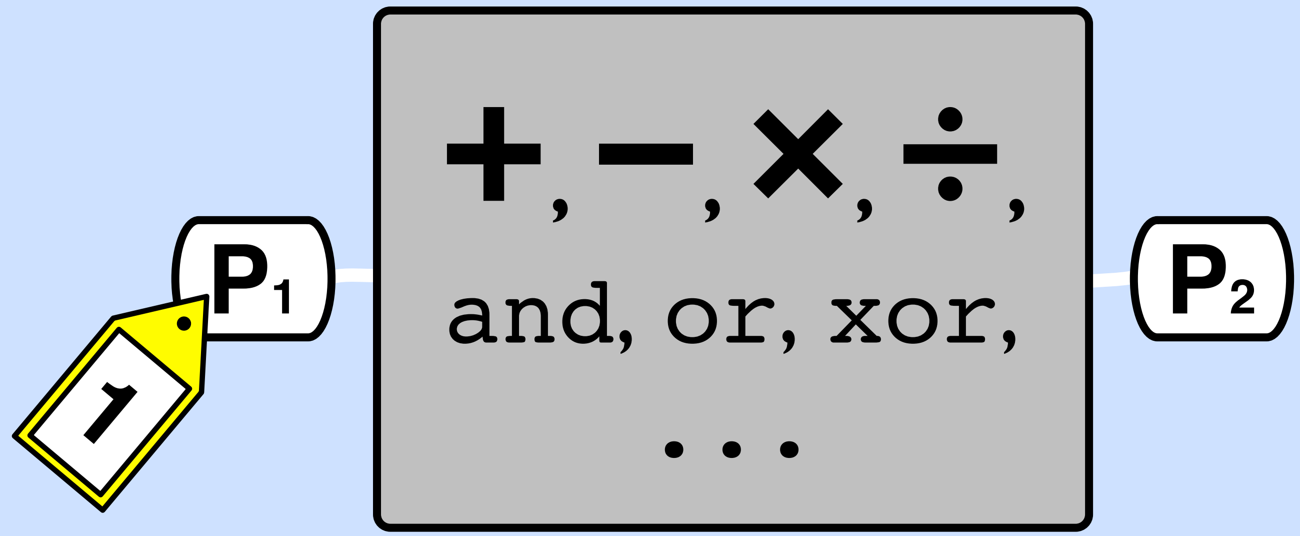



Should the result be tainted?
If so, how?

- Propagation must take into account both operation semantics and programmer intent
- Our policy is based on knowledge of C/C++/assembly and patterns observed in real software

# 2 Propagating taint marks

Overview

**Addition, Subtraction**

AND

Multiplication, Division, OR, XOR

## A +/– B = C

| A | B | C |
| --- | --- | --- |
| 1 | | 1 |
| | 1 | 1 / no taint |
| | ••• | |

Most common use of addition and subtraction is to add or subtract a pointer and an offset

# 2 Propagating taint marks

- Overview
- Addition, Subtraction
- **AND**
- Multiplication, Division, OR, XOR

## A & B = C

| A | B | C |
|---|---|---|
| 1 | | 1 or no taint |
| | ••• | |

The result of anding a pointer and a mask should be treated differently depending on the value of the mask

`c = a & 0xffffff00` - base address

`c = a & 0x000000ff` - offset

# 2 Propagating taint marks

Overview

Addition, Subtraction

AND

Multiplication, Division, OR, XOR

We found zero cases where the result of any of these operations was a pointer

# 3 Checking taint marks

When memory is accessed through a pointer:
compare the memory taint mark and the pointer taint mark

| Pointer | Memory | IMA? |
|---|---|---|
| 2 | 2 | no |
| 1 | 2 | yes |
| 3 | | yes |
| | 3 | yes |
| | | yes |

# Preventing IMAs

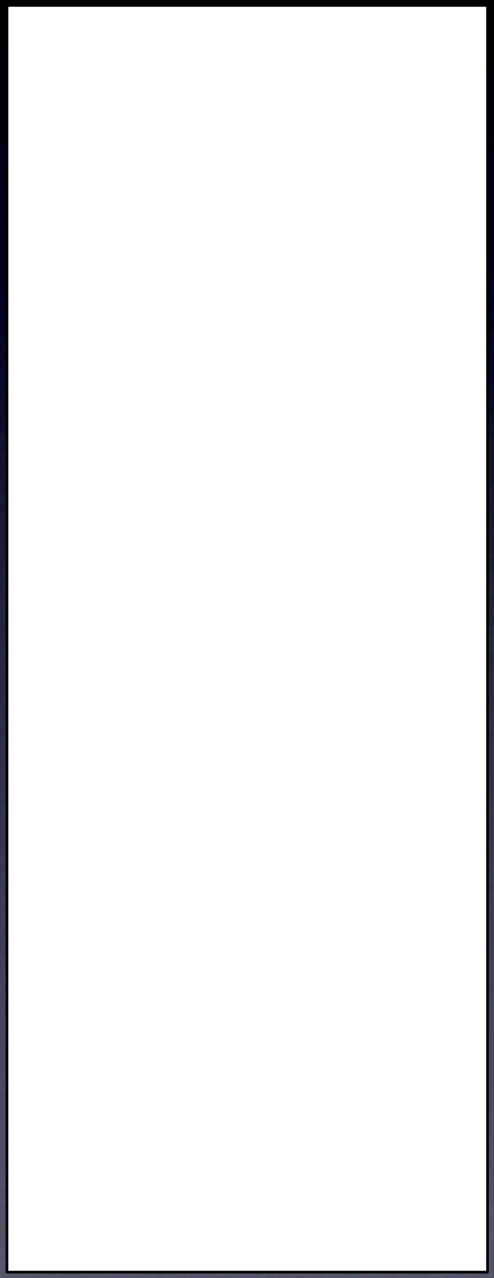
```
  void main() {
1. int *np, n, i, *buf;

2. np = &n;

3. printf("Enter size: ");
4. scanf("%d", np);

5. buf = malloc(n * sizeof(int));

6. for(i = 0; i <= n; i++)
7.   *(buf + i) = rand()%10;
   ...
}
```



# Preventing IMAs

```
void main() {
int *np, n, i, *buf;

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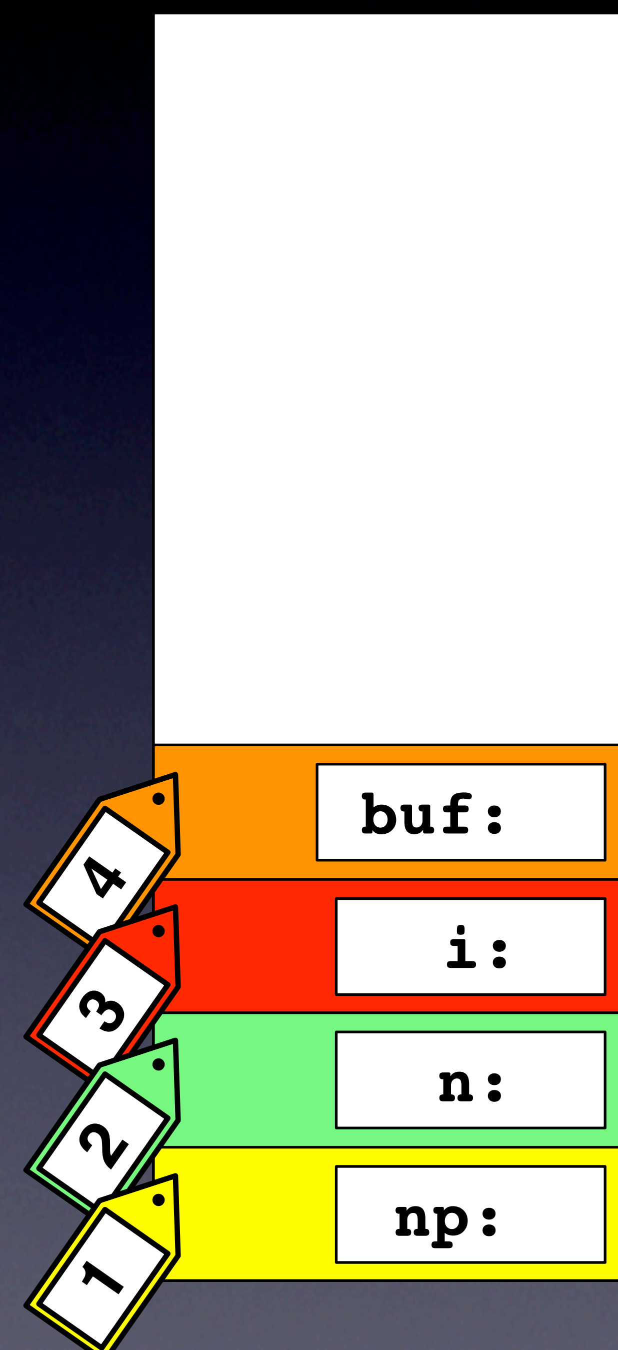

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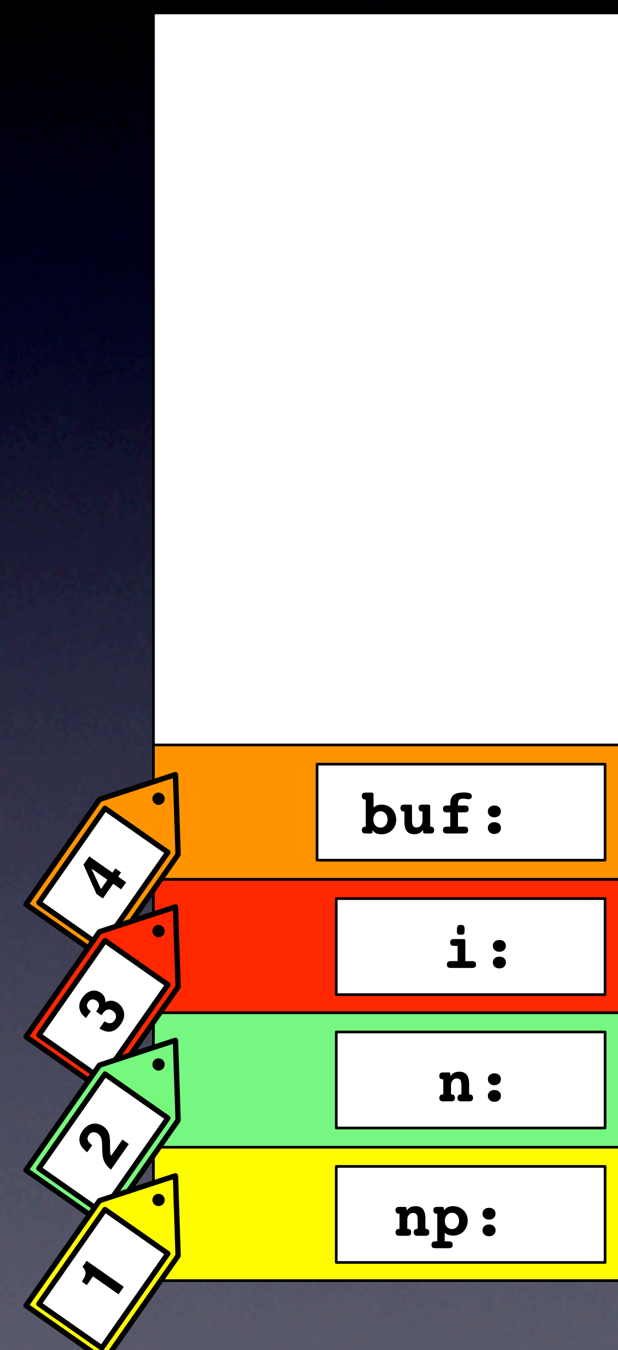

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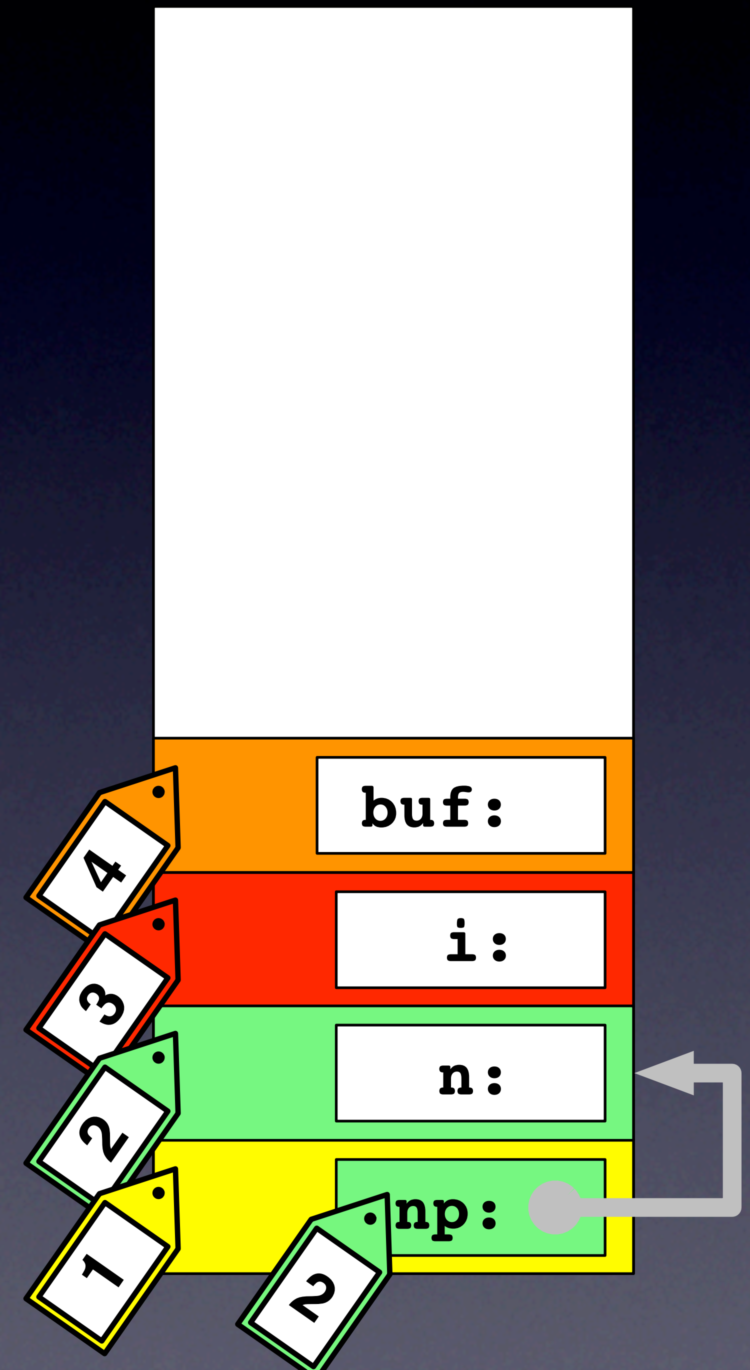

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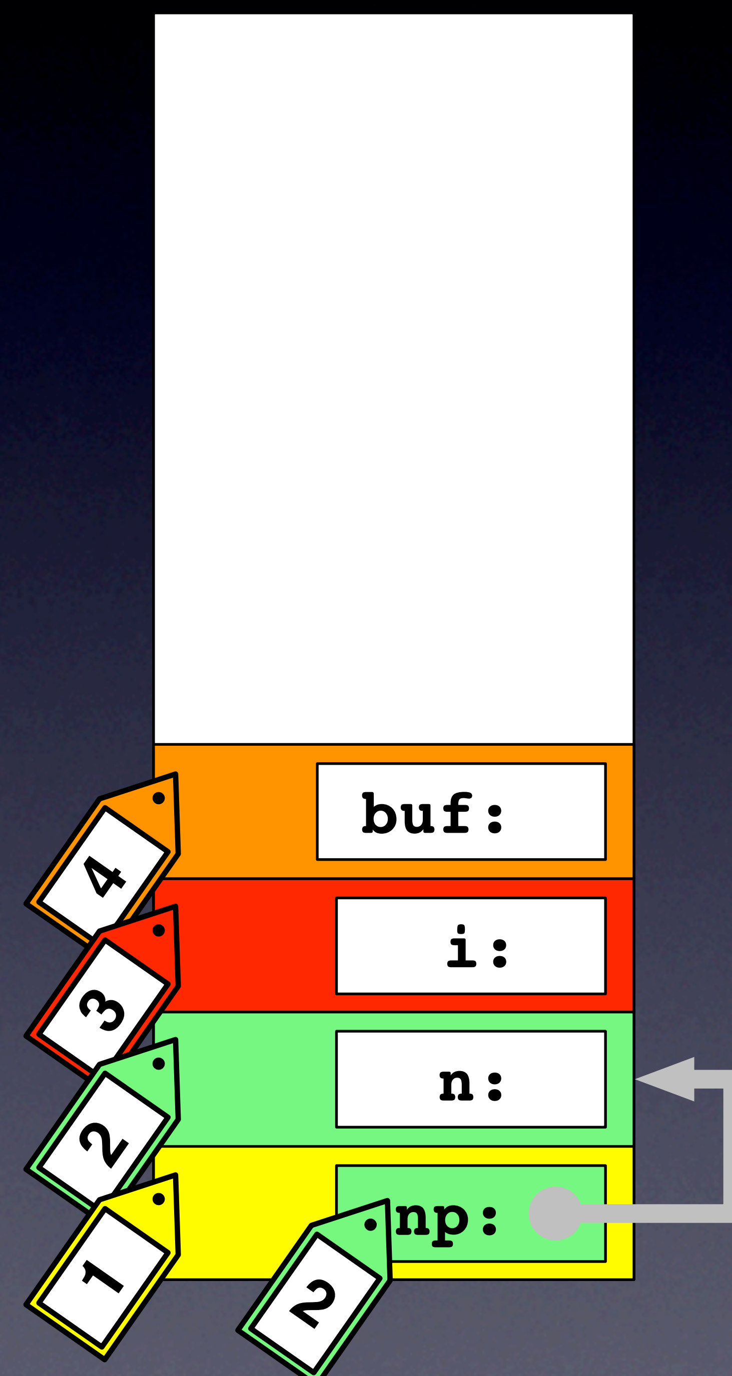

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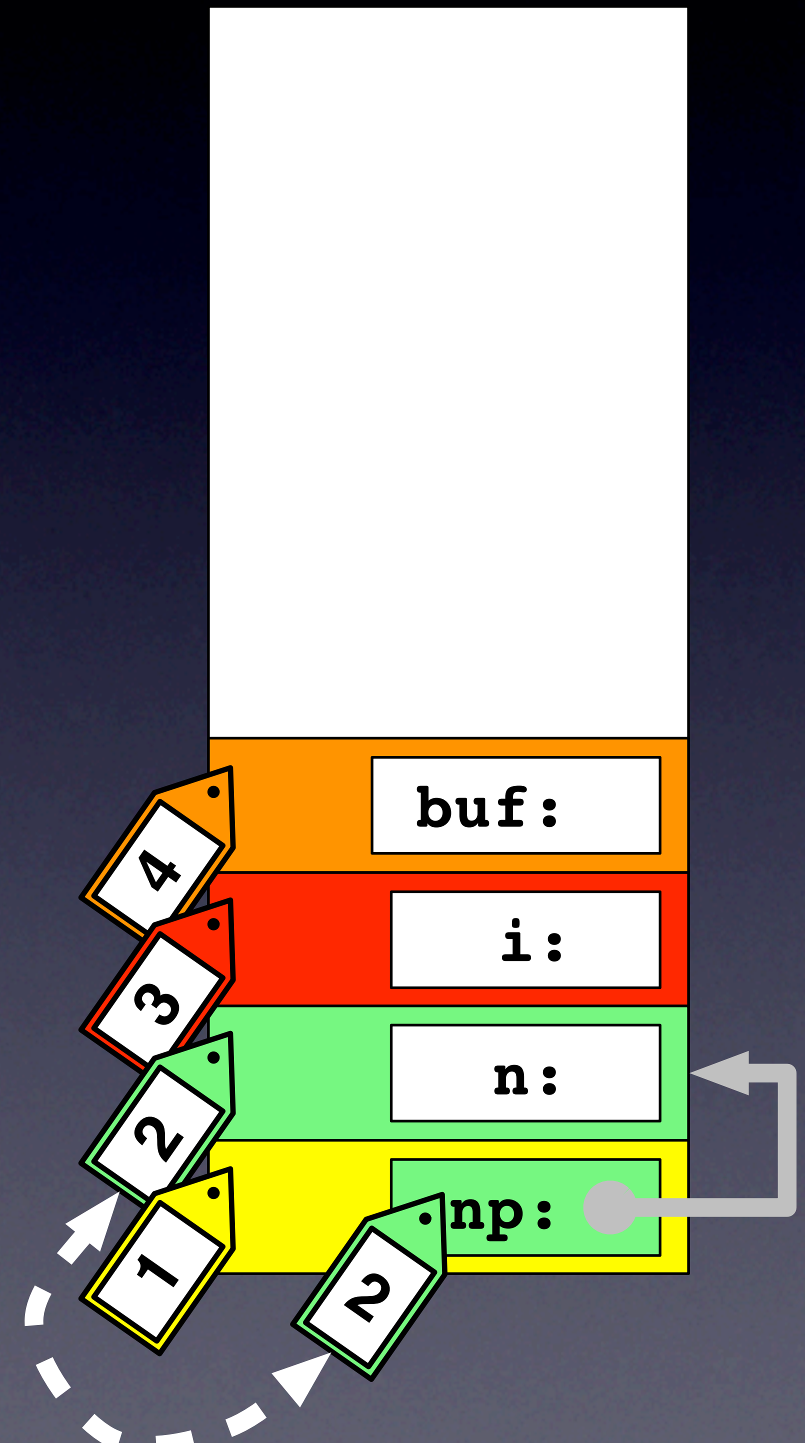

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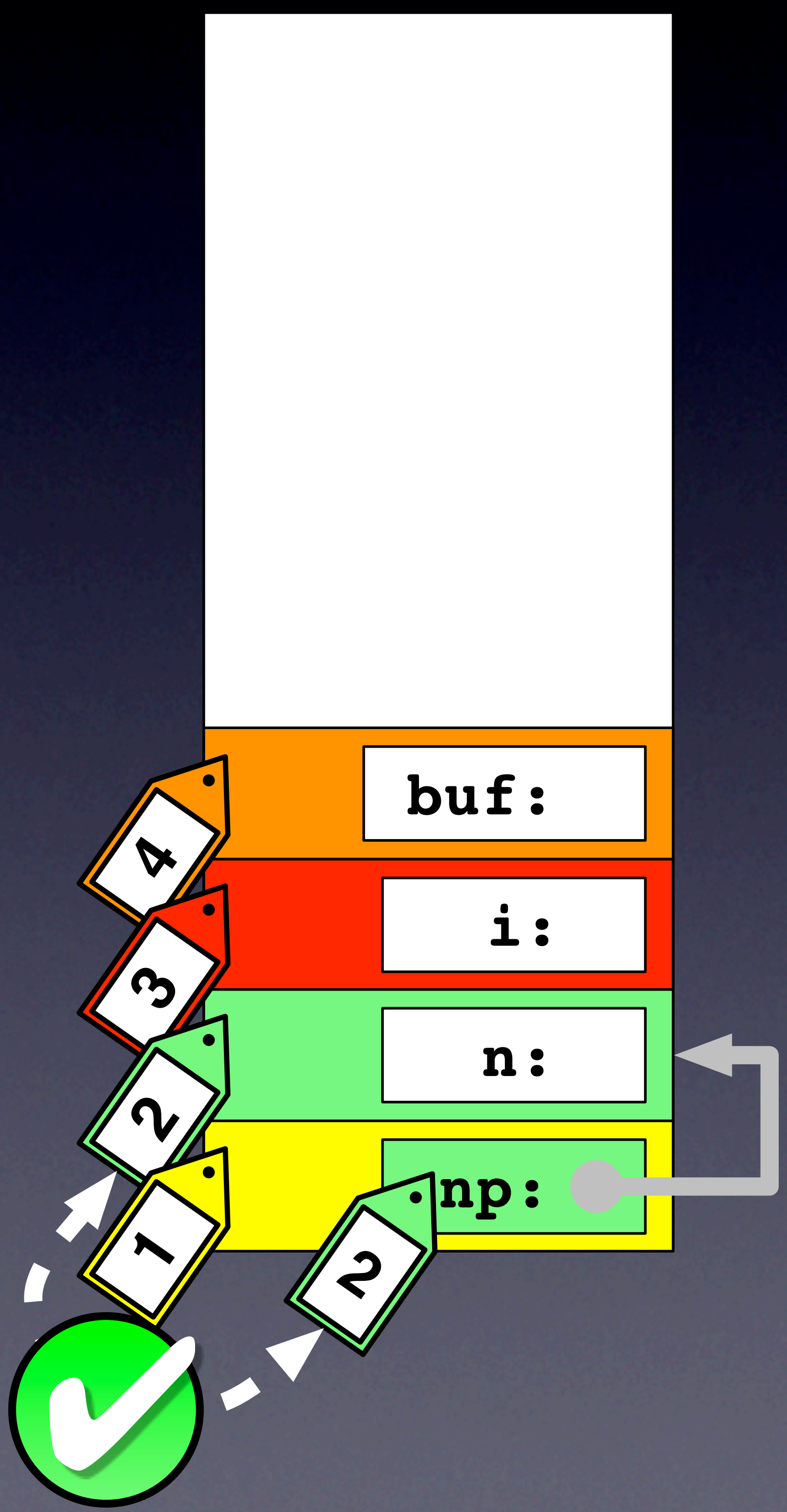

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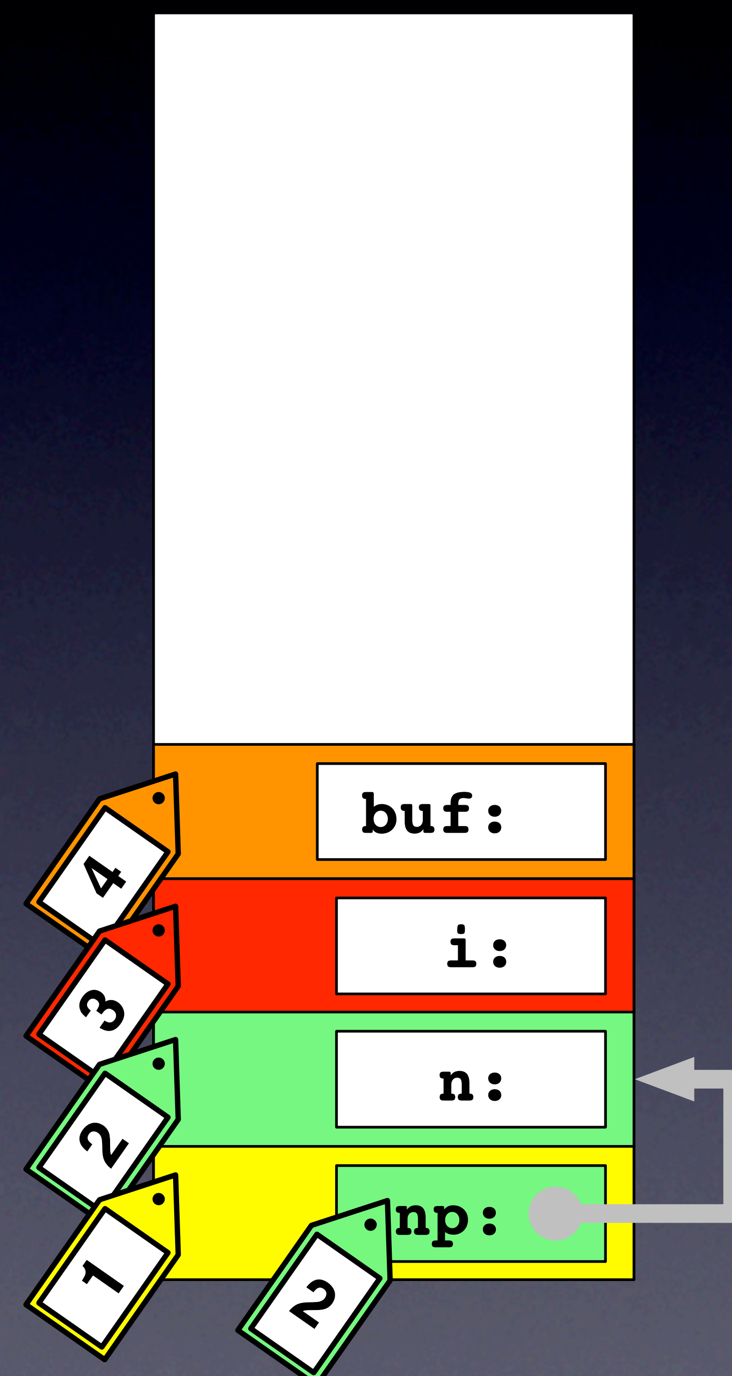

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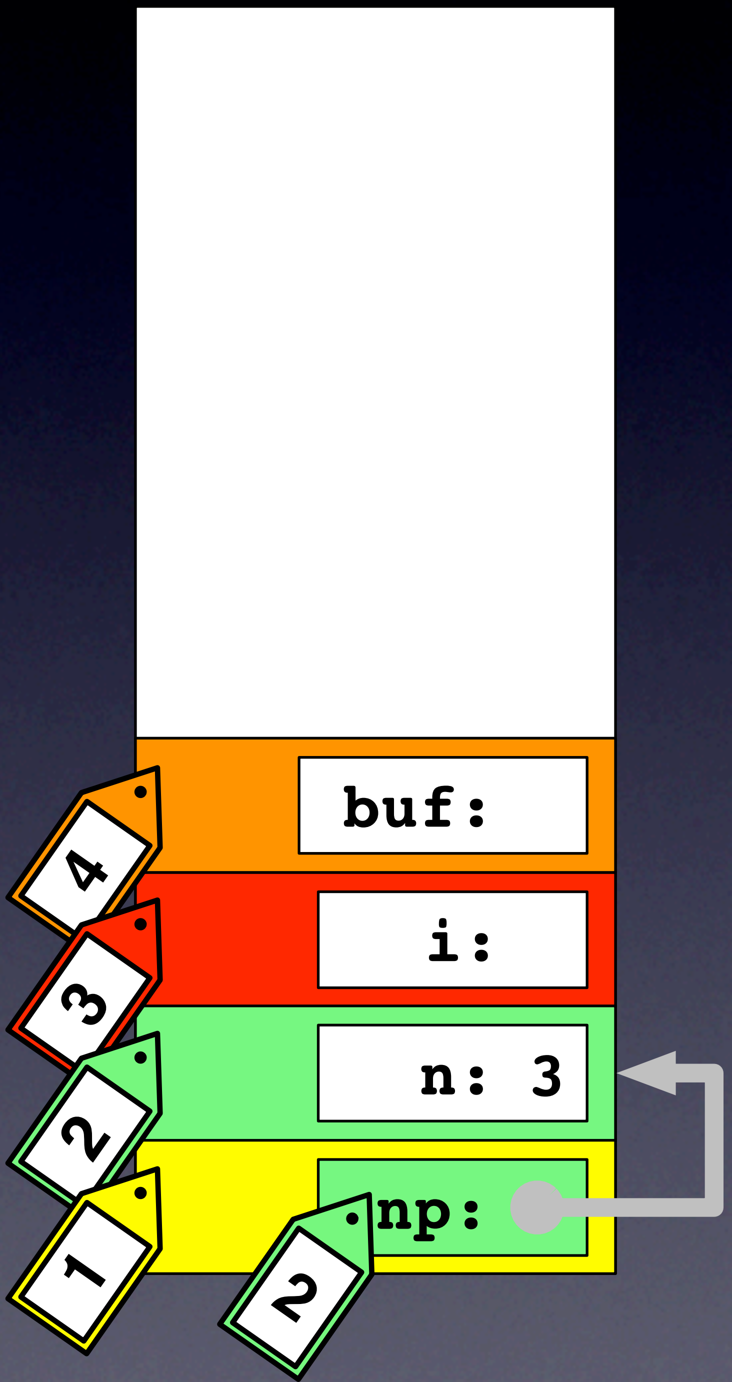

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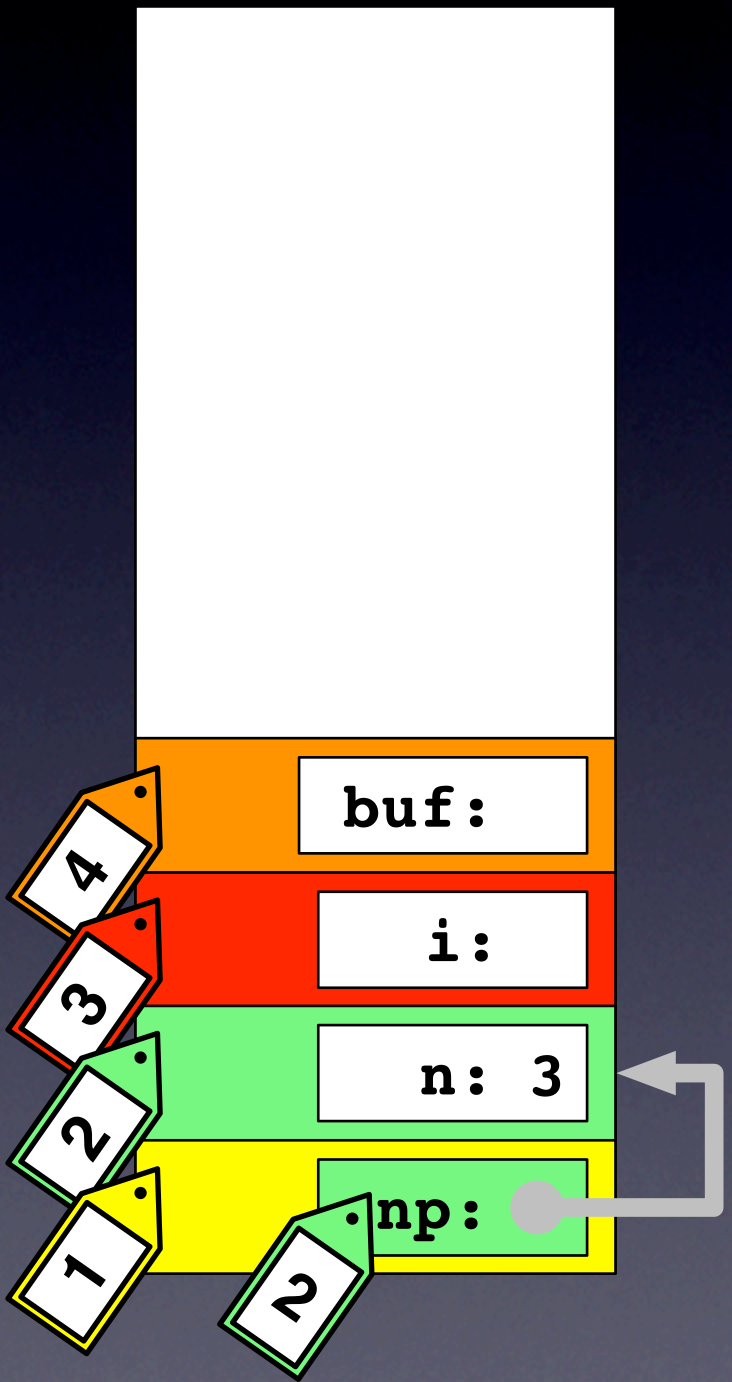

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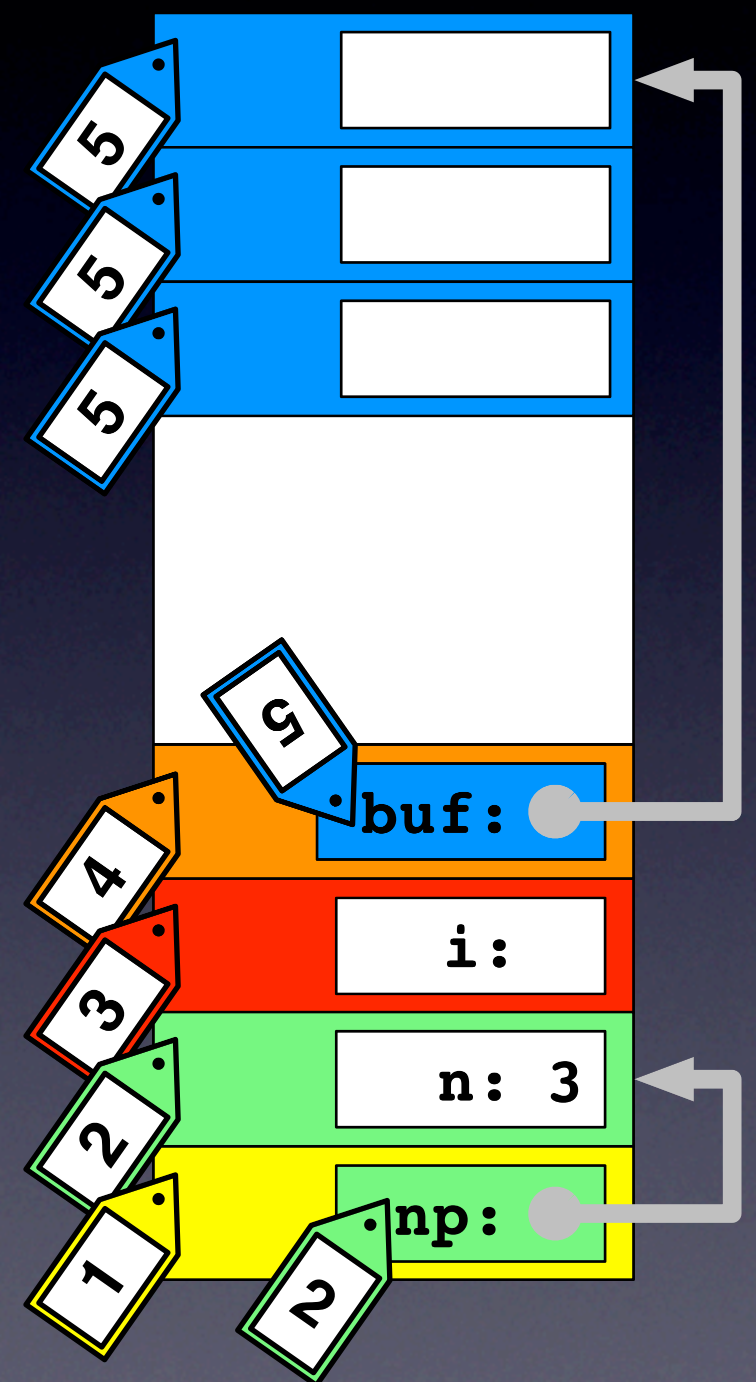

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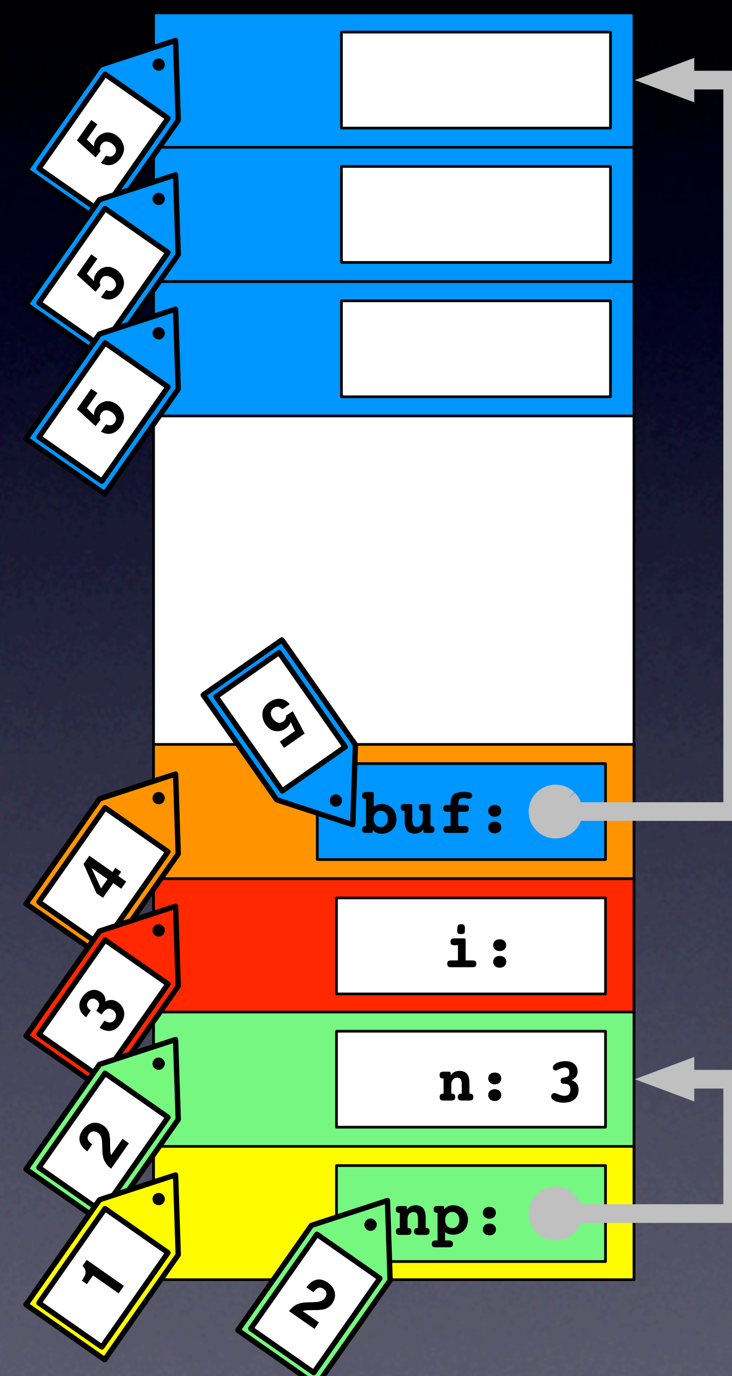

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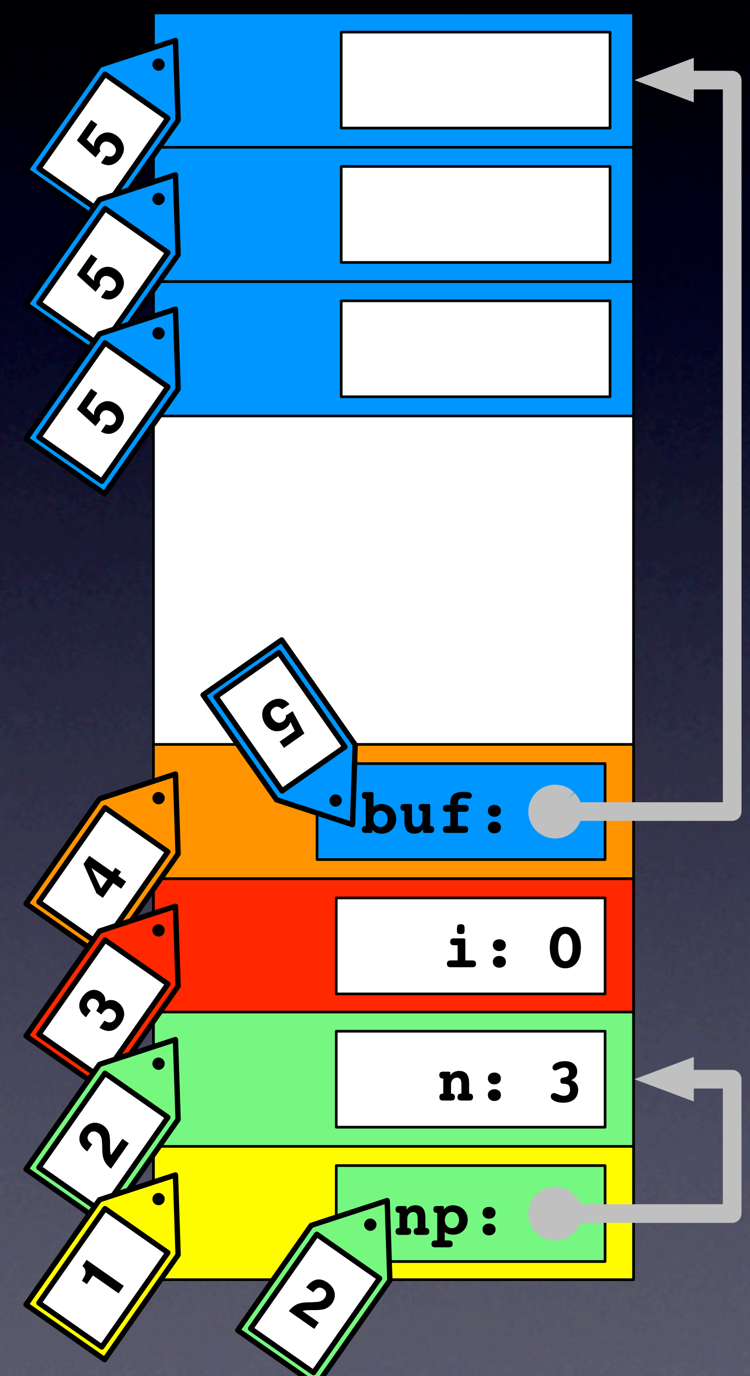

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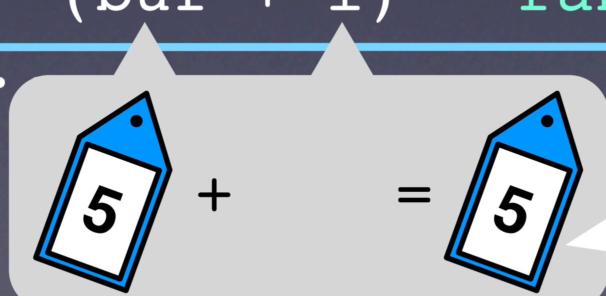


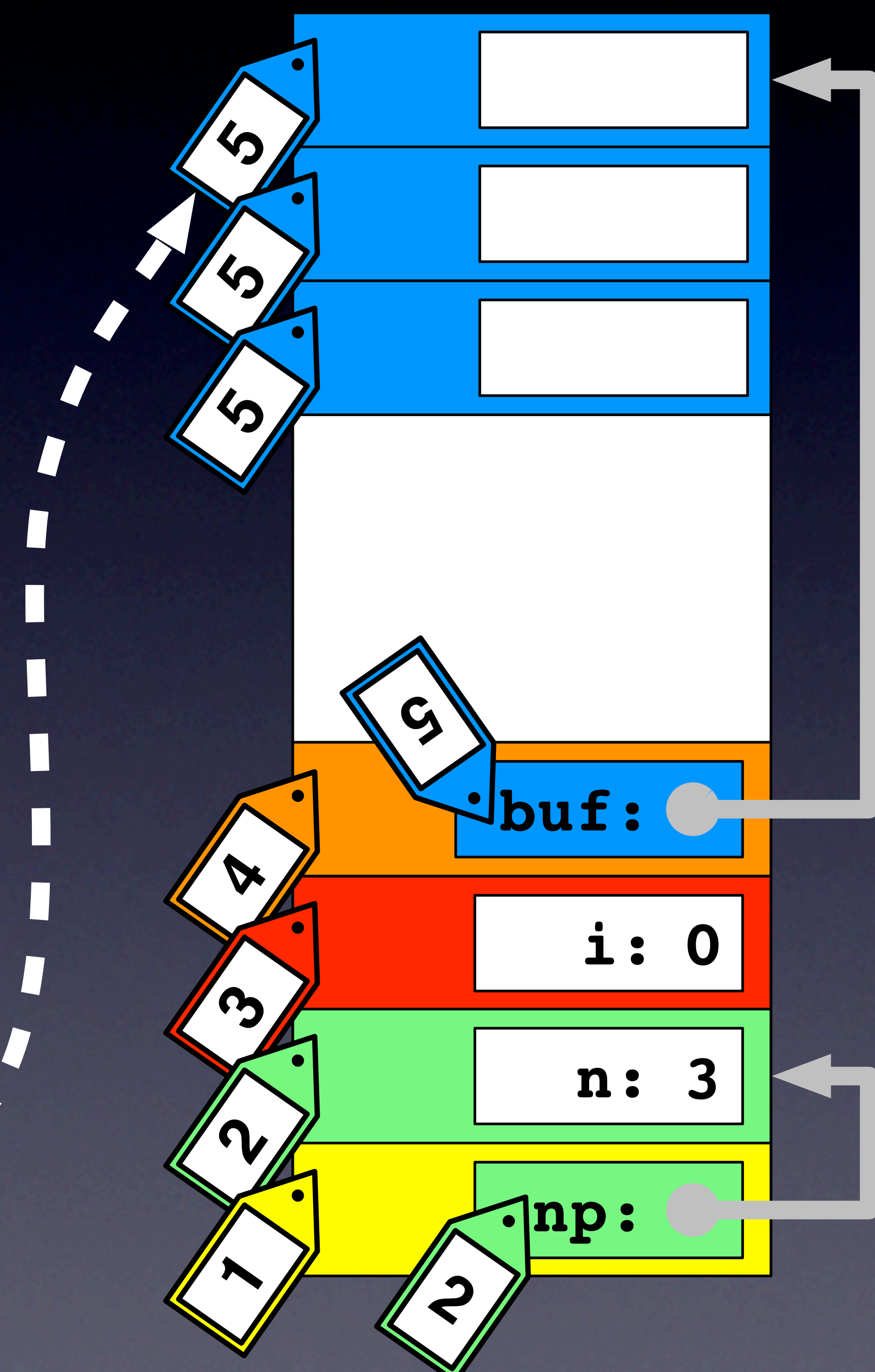

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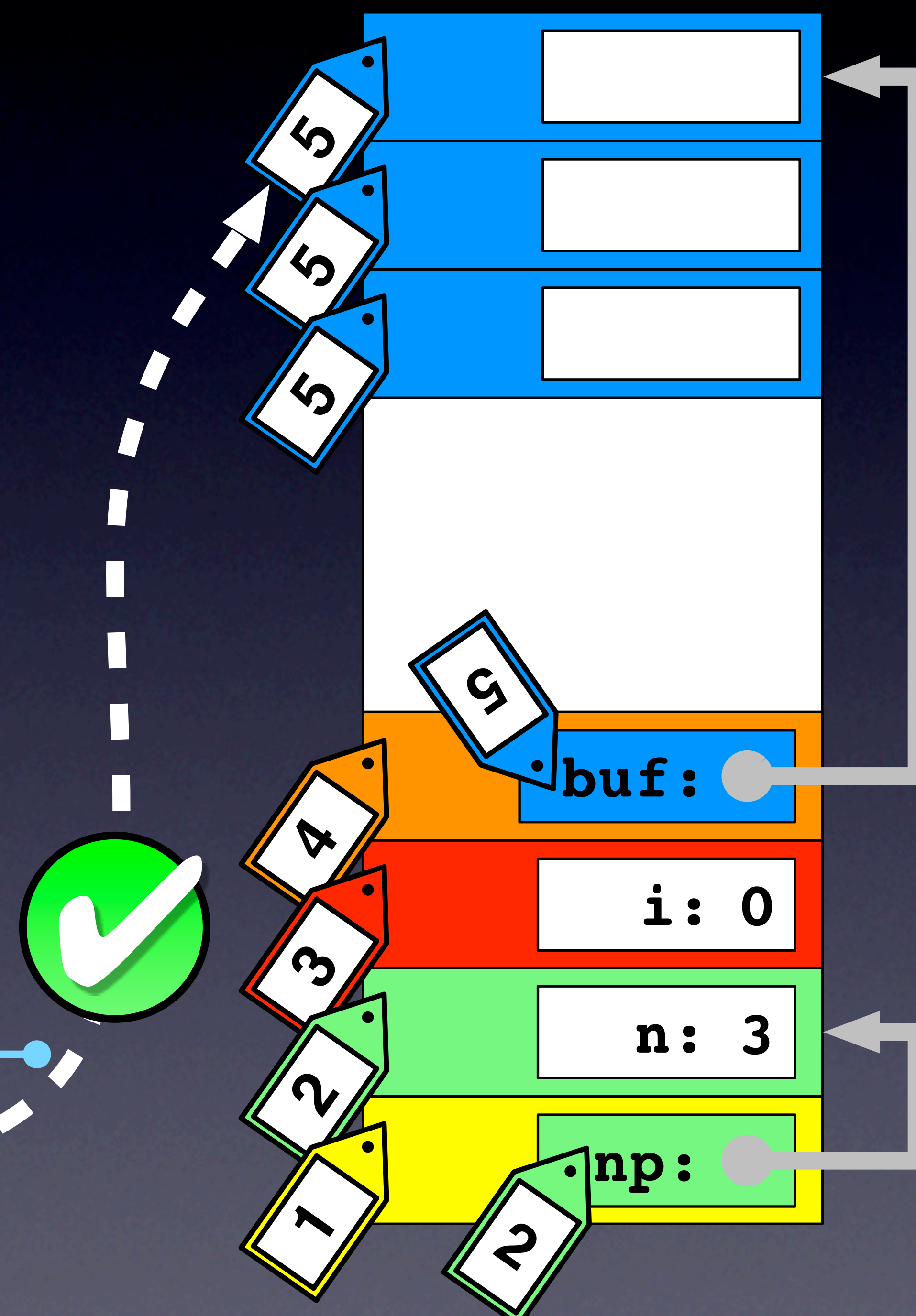

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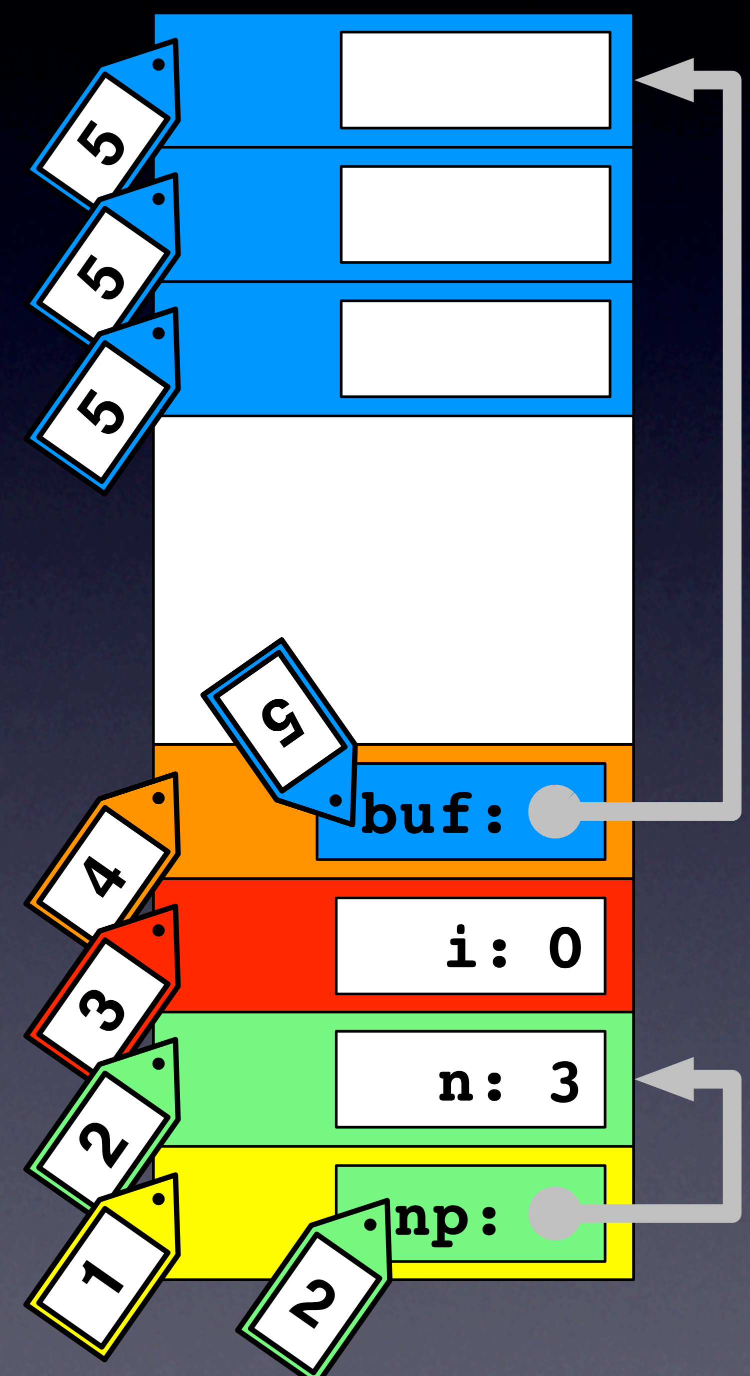

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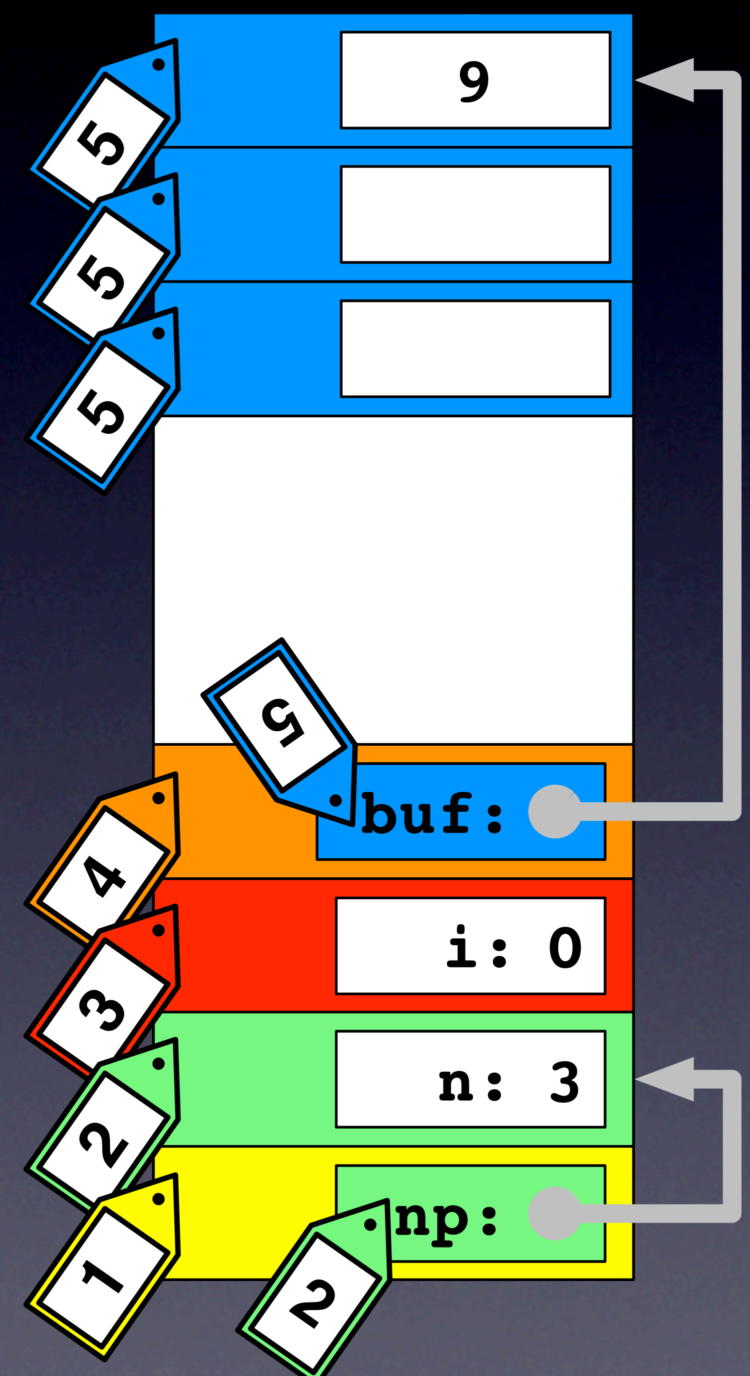

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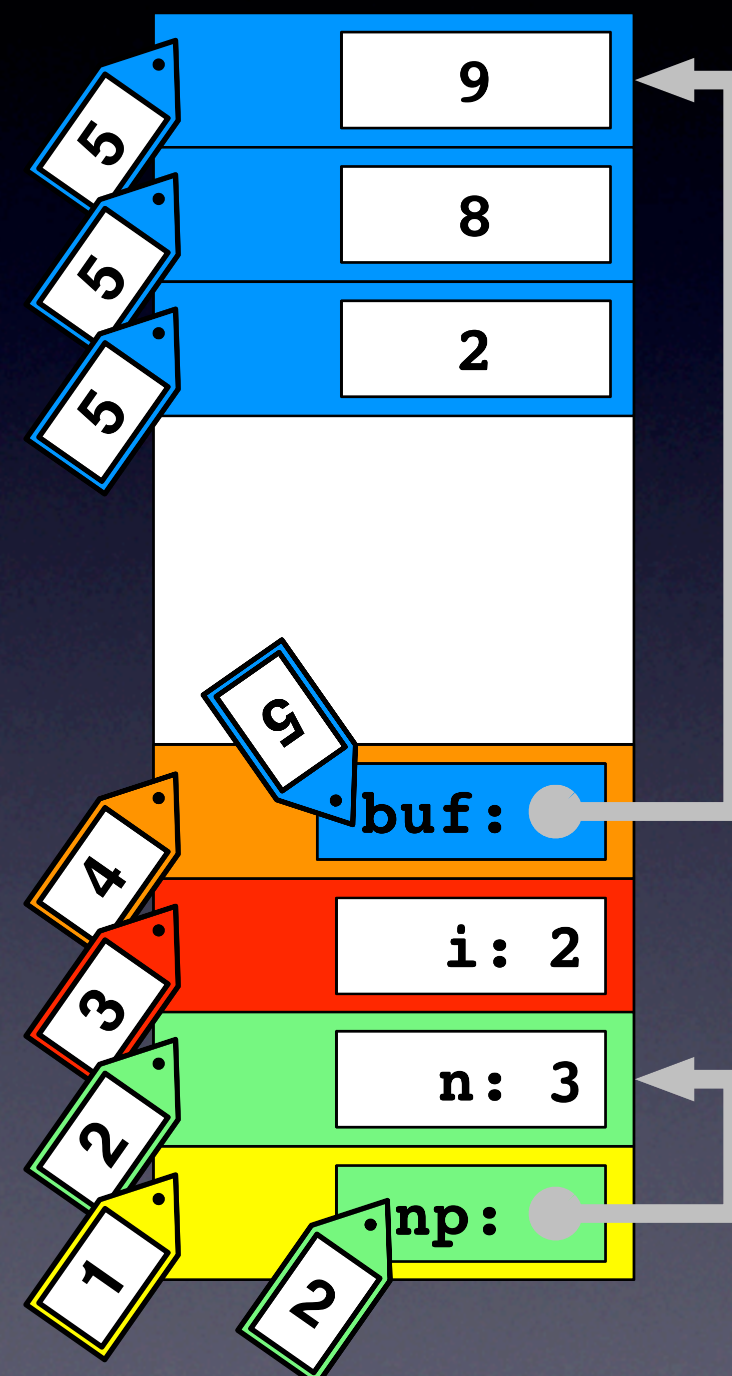

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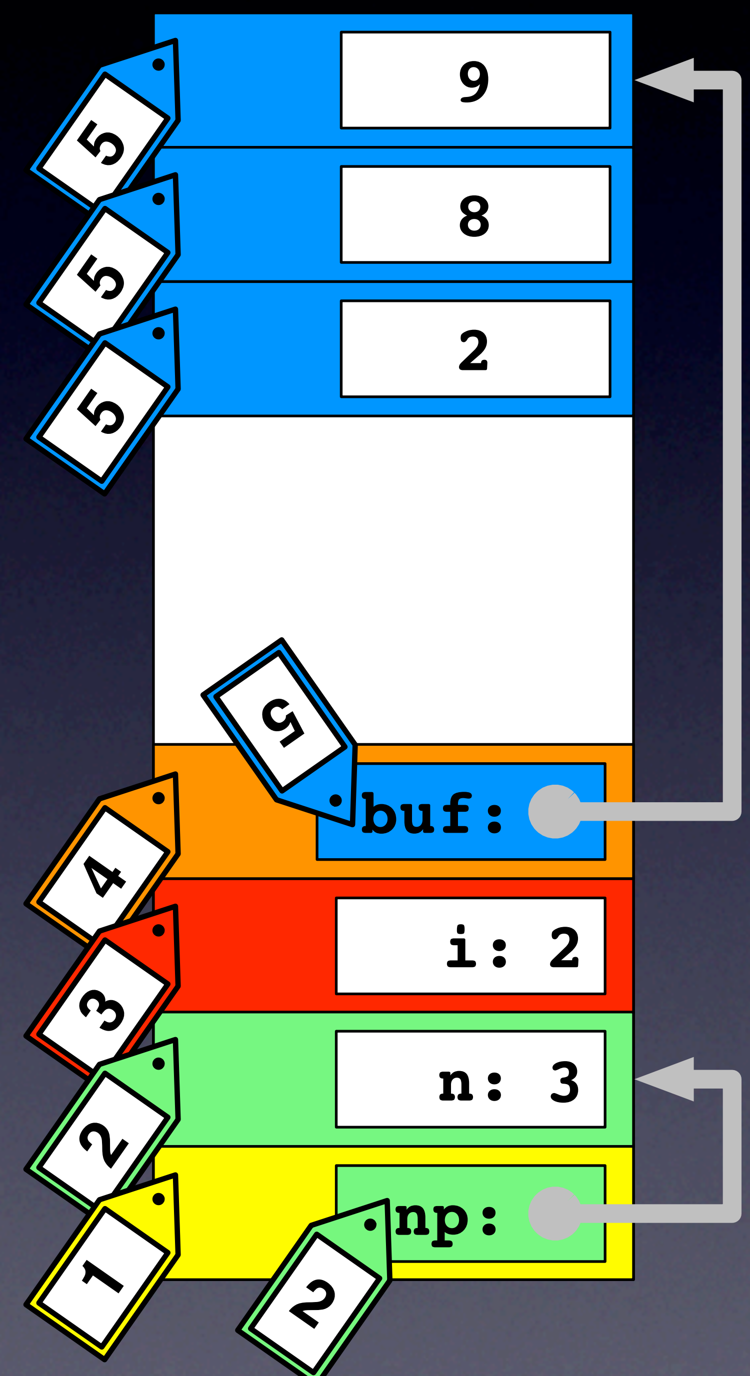

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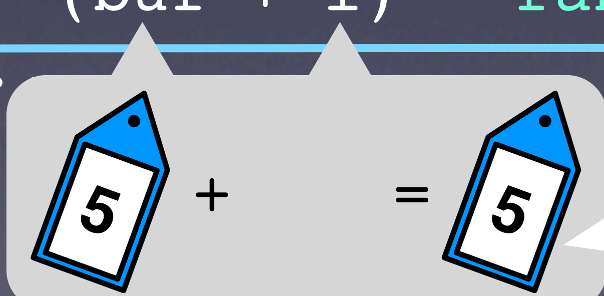


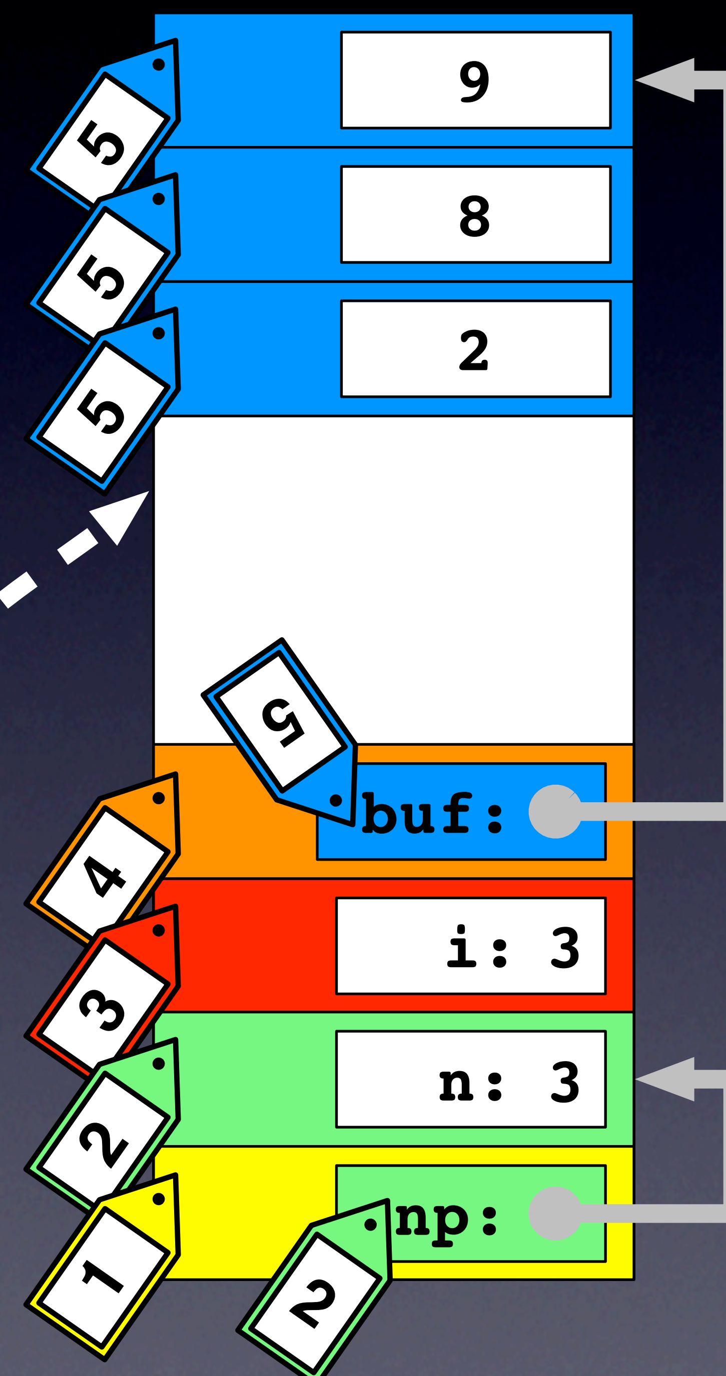

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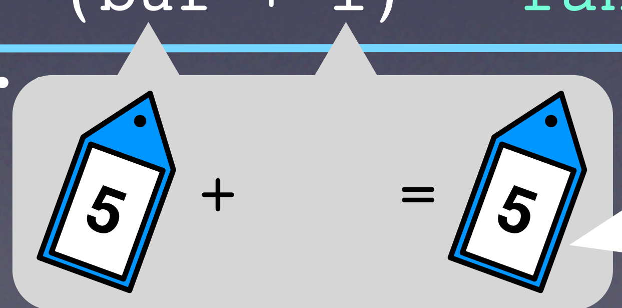


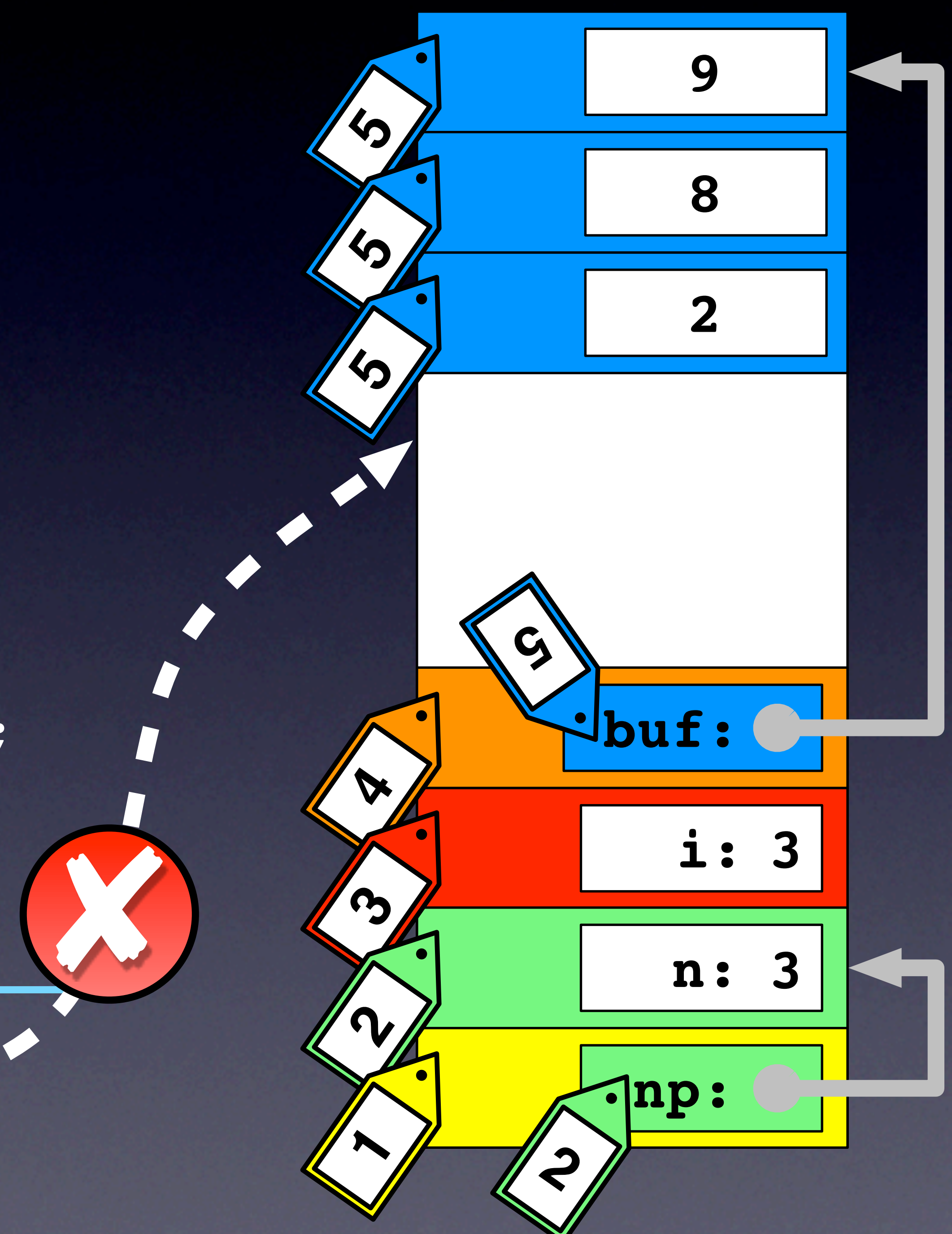

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An unlimited number of taint marks makes a hardware implementation infeasible

- increases the overhead (time and space)
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➡ Assign taint marks from a limited, reusable pool

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## ⚠ IMAs are detected probabilistically

With an random assignment of *n* taint marks the detection probability is:

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1. The technique can be tuned by increasing or decreasing the number of taint marks

2. In practice the approach is successful with only a small number (2) of taint marks

# Empirical evaluation

RQ1: Is the efficiency of our approach sufficient for it to be applied to deployed software?

RQ2: What is the effectiveness of our technique when using limited number of taint marks?

# RQ1: experimental method

- Hardware implementation
  - Cycle accurate simuator (SESC)
  - Treat taint marks as first class citizens
- Subjects
  - SPEC CPU2000 benchmark (12 applications)
- Calculate the overhead imposed by our approach for each subject application

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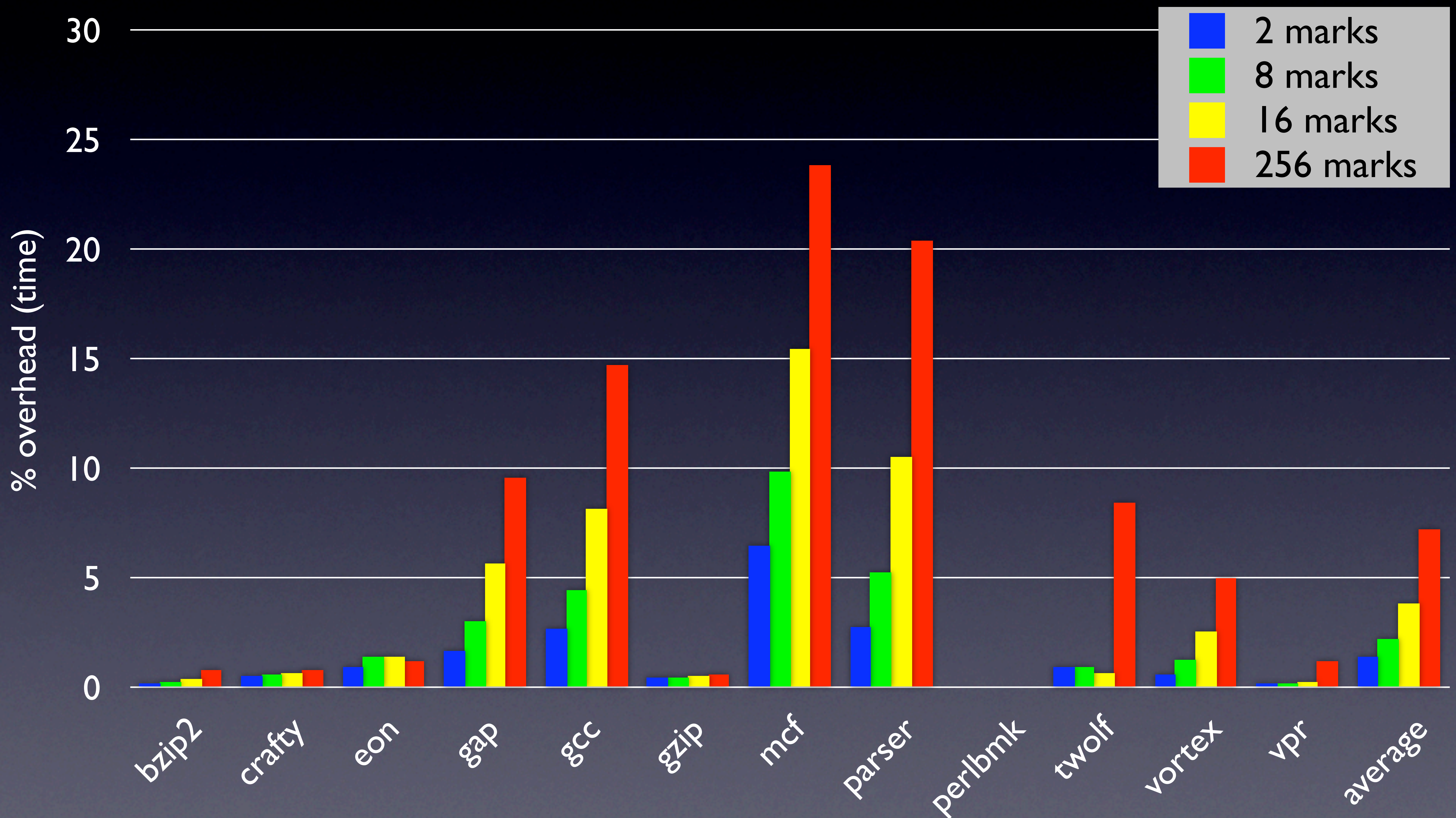
Current implementation assigns taint marks only to dynamically allocated memory, but propagation and checking are fully implemented

# RQ1: results



2 marks
8 marks
16 marks
256 marks
% overhead (time)
30
25
20
15
10
5
0
bzip2
crafty
eon
gap
gcc
gzip
mcf
parser
perlbmk
twolf
vortex
vpr
average

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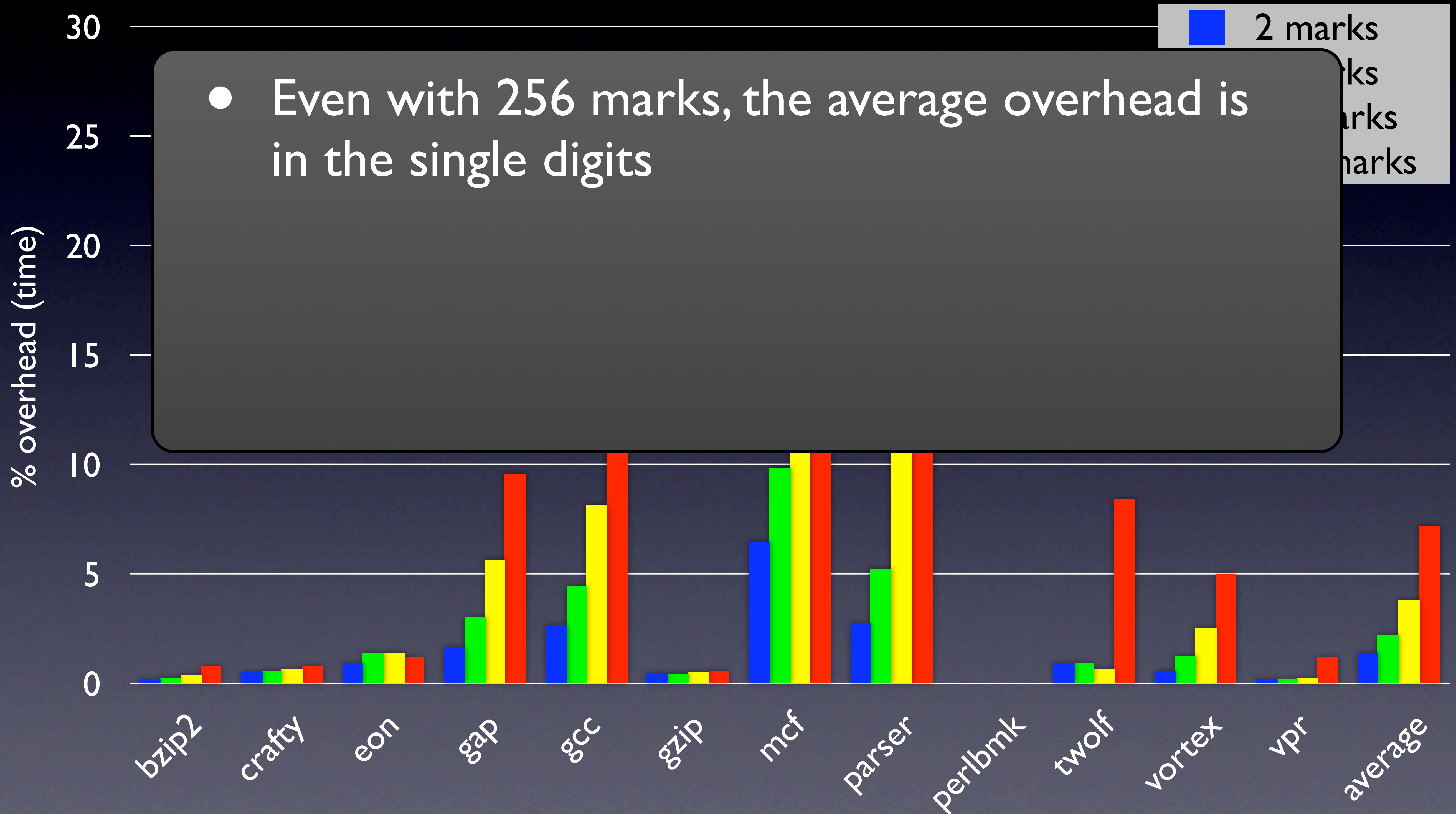


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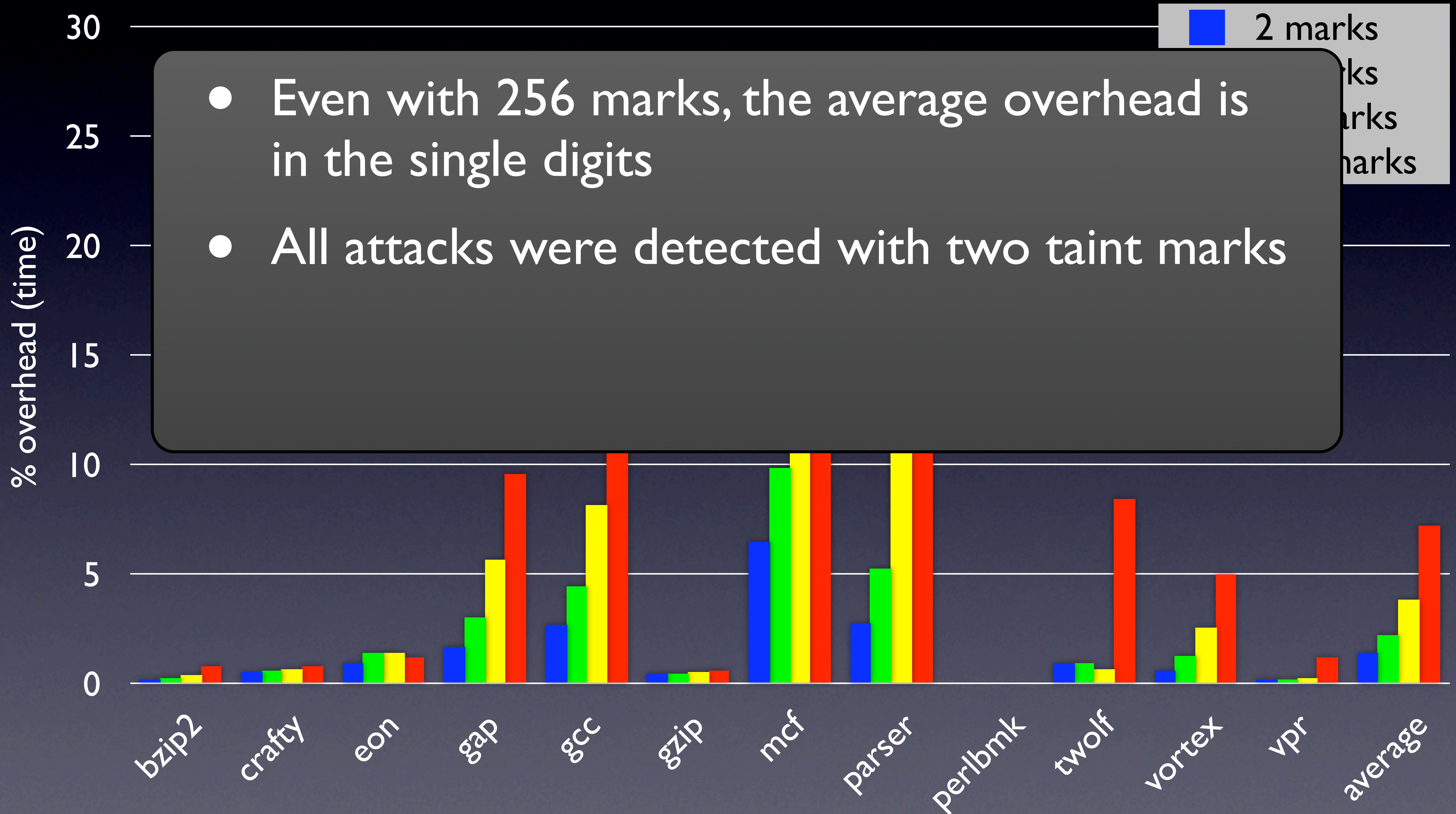


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# RQ1: results

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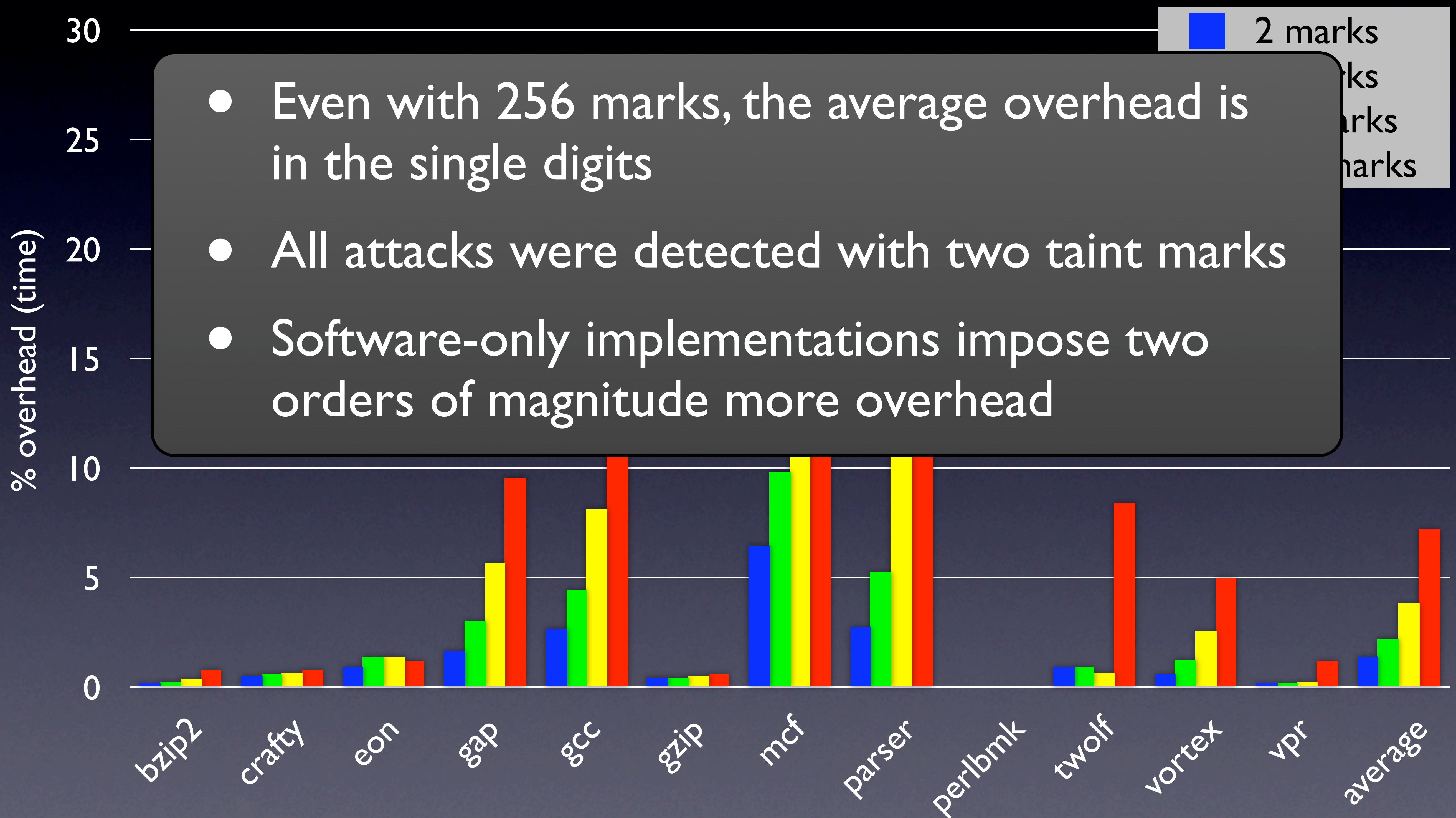
- All attacks were detected with two taint marks
- Software-only implementations impose two orders of magnitude more overhead



# RQ2: experimental method

- Software implementation
  - Binary instrumenter (Pin)
  - Use instrumentation to assign, propagate, and check taint marks
- Subjects
  - SPEC CPU2000 benchmark (12 applications)
  - 5 applications with 7 known IMAs
- Run both each applications protected by our software implementation and check that only the known illegal memory accesses are detected (5 times)

# RQ2: results

## Applications with known IMAs

| Application | IMA location | Type | Detected |
|---|---|---|---|
| bc-1.06 | more_arrays: 177 | buffer overflow | ✔ (5/5) |
| bc-1.06 | lookup: 577 | buffer overflow | ✔ (5/5) |
| gnupg-1.4.4 | parse_comment: 2095 | integer overflow | ✔ (5/5) |
| mutt-1.4.2.li | utf8_to_utf7: 199 | buffer overflow | ✔ (5/5) |
| php-5.2.0 | php_char_to_str_ex: 3152 | integer overflow | ✔ (5/5) |
| pine-4.44 | rfc882_cat: 260 | buffer overflow | ✔ (5/5) |
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## SPEC Benchmarks ("IMA free")

| Application | IMA location | Type | Detected |
|---|---|---|---|
| vortex | SendMsg: 279 | null-pointer dereference | ✔ (5/5) |

# Future work

- Complete implementation that handles static memory
- Additional experiments with a wider range of IMAs
- Further optimization of the hardware implementation

# Conclusions

- Definition of an approach for preventing illegal memory accesses in deployed software
  - uses dynamic taint analysis to protect memory
  - uses probabilistic detection to achieve acceptable overhead
- Empirical evaluation showing that the approach
  - is effective at detecting IMA in real applications
  - can be implemented efficiently in hardware