Buffer Overflow Detection using Abstract Interpretation

(Week 10)

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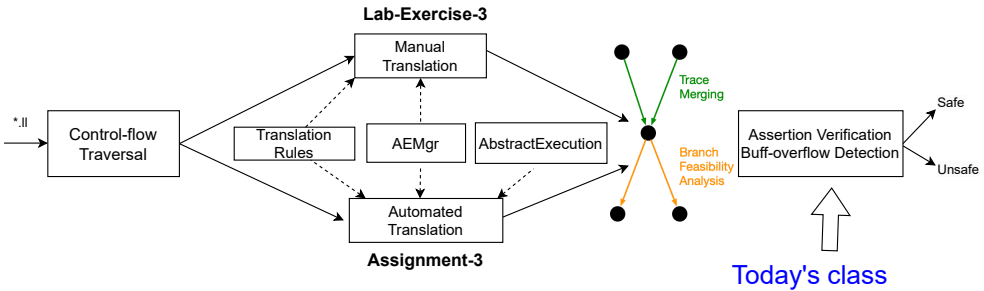
Today’s class



Buffer Overflows

Definition (Buffer Overflow)

Given a buffer `buf` of `sz` bytes allocated in memory, an overflow occurs if an access offset `off` is used to access `buf` at or beyond its boundary, i.e., `off` $\geq$ `sz`.

- A buffer overflow vulnerability occurs when a program exceeds the capacity of a fixed-length memory block (buffer) by reading from or writing more data to it than it was designed to hold.
- Excess (overflowed) data can disrupt nearby memory, causing system errors or unauthorised code execution if manipulated by malicious attackers.

Top ($\top$) and Bottom ($\bot$) and Narrowing Without Loop Bounds

- The default value of an `AbstractValue` is $\langle \bot, \bot \rangle$, consisting of an empty interval and an empty address set (if a variable is not found in maps σ or δ).
- The `AbstractValue` of a variable will be set or **initialized as** $\langle \top, \top \rangle$ if this variable is **a program input** (e.g., arguments of the main function), representing all possible values.
- For a while loop without an explicit bound (e.g., `while(true){...}`), narrowing cannot be performed effectively; it remains a widening over-approximation.
- We will need to handle several external APIs (e.g., `memcpy`-like API without function bodies) in `Assignment-3`.

Example 1: Struct and Array

```c
#include <stdio.h>
#include <stdlib.h>
#define NFT_LEN 16
typedef struct {
    char buffer[8];
} nft_set_elem;
void nft_set_elem_init(nft_set_elem *elem,
                       int len) {
    // Some initialization code is omitted here
    elem->buffer[len - 1] = '\0';
}
int main() {
    // Call the initialization function
    nft_set_elem elem;
    nft_set_elem_init(&elem, NFT_LEN);
    return 0;
}
```

- Do we have a buffer overflow?

Example 1: Struct and Array

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #define NFT_LEN 16
4  typedef struct {
5      char buffer[8];
6  } nft_set_elem;
7  void nft_set_elem_init(nft_set_elem *elem,
8                         int len) {
9      // Some initialization code is omitted here
10     elem->buffer[len - 1] = '\0';
11 }
12 int main() {
13     // Call the initialization function
14     nft_set_elem elem;
15     nft_set_elem_init(&elem, NFT_LEN);
16     return 0;
17 }
```

- Do we have a buffer overflow?
- Yes, at Line 10.
- The value of `len` $-$ `1` is 15, which is out of bounds for the buffer `elem` $\rightarrow$ `buffer` which has a size of 8.

Example 2: Struct and Array

```
1  #include <stdio.h>
2  #include <string.h>
3  #define NFT_LEN 16
4  typedef struct {
5    char buffer[8];
6  } nft_set_elem;
7  void nft_set_elem_init(nft_set_elem *elem,
8                         int len) {
9    // Ensure we do not overflow the buffer
10   if (len > sizeof(elem->buffer))
11     elem->buffer[sizeof(elem->buffer)-1] = '\0';
12   else
13     elem->buffer[len - 1] = '\0';
14 }
15 int main() {
16   // Call the initialization function
17   nft_set_elem elem;
18   nft_set_elem_init(&elem, NFT_LEN);
19   return 0;
20 }
```

- Do we have a buffer overflow?

Example 2: Struct and Array

```
1  #include <stdio.h>
2  #include <string.h>
3  #define NFT_LEN 16
4  typedef struct {
5    char buffer[8];
6  } nft_set_elem;
7  void nft_set_elem_init(nft_set_elem *elem,
8                         int len) {
9    // Ensure we do not overflow the buffer
10   if (len > sizeof(elem->buffer))
11     elem->buffer[sizeof(elem->buffer)-1] = '\0';
12   else
13     elem->buffer[len - 1] = '\0';
14 }
15 int main() {
16   // Call the initialization function
17   nft_set_elem elem;
18   nft_set_elem_init(&elem, NFT_LEN);
19   return 0;
20 }
```

- Do we have a buffer overflow?
- No
- Line 12 ensures that the buffer is safely accessed. The buffer is not exceeded, and the string ends with a null character.

Example 3: Struct and Array

```
1  #include <stdio.h>
2  struct Data {
3    int value;
4    char name[5];
5  };
6  void process_data_array(struct Data *data_array,
7                          int size) {
8    for (int i = 0; i < size; i++) {
9      for (int j = 0; j < size; j++) {
10       data_array[i].name[j] = 'A';
11     }
12     data_array[i].name[size-1] = '\0';
13   }
14 }
15 int main() {
16   struct Data data_array[10];
17   process_data_array(data_array, 10);
18   return 0;
19 }
```

- Do we have a buffer overflow?

Example 3: Struct and Array

```
1  #include <stdio.h>
2  struct Data {
3    int value;
4    char name[5];
5  };
6  void process_data_array(struct Data *data_array,
7                          int size) {
8    for (int i = 0; i < size; i++) {
9      for (int j = 0; j < size; j++) {
10       data_array[i].name[j] = 'A';
11     }
12     data_array[i].name[size-1] = '\0';
13   }
14 }
15 int main() {
16   struct Data data_array[10];
17   process_data_array(data_array, 10);
18   return 0;
19 }
```

- Do we have a buffer overflow?
- Yes, at Line 10 and Line 12
- The loop `for (int j = 0; j < size; j++)` writes past the end of the `name` array, as `size` is larger than the size of `name` array.

Example 4: Loop

```c
#include <stdio.h>
#define BUF_LEN 20
void handle_buffer(char *input) {
  char buffer[BUF_LEN];
  for(int i = 0; i < 30; i++) {
    buffer[i] = input[i];
    if (input[i] == '\0')
        break;
  }
  buffer[BUF_LEN-1] = '\0';
  printf("Buffer content: %s\n", buffer);
}
int main() {
  char input[30] = "ABCDEFGHIJKLMNOPQRSTUVWXYZ123";
  handle_buffer(input);
  return 0;
}
```

- Do we have a buffer overflow?

Example 4: Loop

```
1  #include <stdio.h>
2  #define BUF_LEN 20
3  void handle_buffer(char *input) {
4    char buffer[BUF_LEN];
5    for(int i = 0; i < 30; i++) {
6      buffer[i] = input[i];
7      if (input[i] == '\0')
8          break;
9    }
10   buffer[BUF_LEN-1] = '\0';
11   printf("Buffer content: %s\n", buffer);
12 }
13 int main() {
14   char input[30] = "ABCDEFGHIJKLMNOPQRSTUVWXYZ123";
15   handle_buffer(input);
16   return 0;
17 }
```

- Do we have a buffer overflow?
- Yes, at Line 6.
- The size of the source buffer `input` is larger than the destination `buffer` when performing an element-wise copying.

Example 5: Loop

```
1  void process_input(char input[5][10]) {
2    char buffer[50];
3    int i, j, k = 0;
4    for (i = 0; i < 5; i++) {
5      for (j = 0; j <= 10; j++) {
6        buffer[k++] = input[i][j];
7      }
8    }
9    buffer[49] = '\0';
10 }
11 int main() {
12   char input[5][10] = {
13     "1234567890",
14     "abcdefghij",
15     "ABCDEFGHIJ",
16     "0987654321",
17     "ZYXWVUTSRQ" };
18   process_input(input);
19   return 0;
20 }
```

- Do we have a buffer overflow?

Example 5: Loop

```
1  void process_input(char input[5][10]) {
2    char buffer[50];
3    int i, j, k = 0;
4    for (i = 0; i < 5; i++) {
5      for (j = 0; j <= 10; j++) {
6        buffer[k++] = input[i][j];
7      }
8    }
9    buffer[49] = '\0';
10 }
11 int main() {
12   char input[5][10] = {
13     "1234567890",
14     "abcdefghij",
15     "ABCDEFGHIJ",
16     "0987654321",
17     "ZYXWVUTSRQ" };
18   process_input(input);
19   return 0;
20 }
```

- Do we have a buffer overflow?
- Yes, at Line 6.
- The loop `for (j = 0; j <= 10; j++)` writes past the end of the `input[i]` array, as the inner loop bound can equal to 10.

Example 6: Loop

```
1  #define BUF_LEN 20
2  bool continue_copying = true;
3  void copy_data(char *input) {
4    char buffer[BUF_LEN];
5    int i = 0;
6    while (continue_copying) {
7      buffer[i] = input[i];
8      i++;
9      if (input[i] == '\0') {
10       continue_copying = false;
11     }
12   }
13   buffer[BUF_LEN-1] = '\0';
14   printf("Buffer content: %s\n", buffer);
15 }
16 int main() {
17   char input[30] = "ABCDEFGHIJKLMNOPQRSTUVWXYZ123";
18   copy_data(input);
19   return 0;
20 }
```

- Do we have a buffer overflow?

Example 6: Loop

```
1  #define BUF_LEN 20
2  bool continue_copying = true;
3  void copy_data(char *input) {
4    char buffer[BUF_LEN];
5    int i = 0;
6    while (continue_copying) {
7      buffer[i] = input[i];
8      i++;
9      if (input[i] == '\0') {
10       continue_copying = false;
11     }
12   }
13   buffer[BUF_LEN-1] = '\0';
14   printf("Buffer content: %s\n", buffer);
15 }
16 int main() {
17   char input[30] = "ABCDEFGHIJKLMNOPQRSTUVWXYZ123";
18   copy_data(input);
19   return 0;
20 }
```

- Do we have a buffer overflow?
- Yes, at Line 7.
- The condition `while (continue_copying)` does not check the buffer size. If the input string is longer than the buffer, it will write past the end of the buffer.
- **Narrowing will not work effectively, as the bound of the loop is not explicit**.

Example 7: Interprocedural

```
1  #define BUFFER_SIZE 10
2  void handle_client_request(char *input,
3                             int index) {
4    int buffer[BUFFER_SIZE] = { 0 };
5    if (index >= 0)
6      buffer[index] = input[index];
7    else
8      printf("ERR: Array index is negative\n");
9  }
10 void process_socket_data(char *input,
11                           int index) {
12   handle_client_request(input, index);
13 }
14 int main(int index) {
15   char inputBuffer[BUFFER_SIZE] = {0};
16   process_socket_data(inputBuffer, index);
17   return 0;
18 }
```

- Do we have a buffer overflow?

Example 7: Interprocedural

```
1  #define BUFFER_SIZE 10
2  void handle_client_request(char *input,
3                             int index) {
4    int buffer[BUFFER_SIZE] = { 0 };
5    if (index >= 0)
6      buffer[index] = input[index];
7    else
8      printf("ERR: Array index is negative\n");
9  }
10 void process_socket_data(char *input,
11                           int index) {
12   handle_client_request(input, index);
13 }
14 int main(int index) {
15   char inputBuffer[BUFFER_SIZE] = {0};
16   process_socket_data(inputBuffer, index);
17   return 0;
18 }
```

- Do we have a buffer overflow?
- Yes, at Line 6.
- The code does not check if `index` is less than `BUFFER_SIZE` in `handle_client_request`. This can lead to a buffer overflow if `index` is 10 or greater.

Example 8: Interprocedural

```
1  #define BUFFER_SIZE 10
2  void handle_client_request(char *input,
3                             int index) {
4    int buffer[BUFFER_SIZE] = { 0 };
5    if (index >= 0 && index < BUFFER_SIZE)
6      buffer[index] = input[index];
7    else
8      printf("ERR: Array index is out of bounds\n");
9  }
10 void process_socket_data(char *input,
11                           int index) {
12   handle_client_request(input, index);
13 }
14 int main(int index) {
15   char inputBuffer[BUFFER_SIZE] = {0};
16   process_socket_data(inputBuffer, index);
17   return 0;
18 }
```

- Do we have a buffer overflow?

Example 8: Interprocedural

```c
#define BUFFER_SIZE 10
void handle_client_request(char *input,
                           int index) {
  int buffer[BUFFER_SIZE] = { 0 };
  if (index >= 0 && index < BUFFER_SIZE)
    buffer[index] = input[index];
  else
    printf("ERR: Array index is out of bounds\n");
}
void process_socket_data(char *input,
                         int index) {
  handle_client_request(input, index);
}
int main(int index) {
  char inputBuffer[BUFFER_SIZE] = {0};
  process_socket_data(inputBuffer, index);
  return 0;
}
```

- Do we have a buffer overflow?
- No
- The code now checks if `index` is within the valid range (0 to `BUFFER_SIZE - 1`) in `handle_client_request`, preventing buffer overflows.

Example 9: Branch

```c
#include "stdbool.h"
int main(int argc) {
  int buf[10];
  int *loc = malloc(sizeof(int));
  int i = argc % 10;
  if (argc == 0) {
    *loc = i;
  } else {
    *loc = ++i;
  }
  int idx = *loc;
  buf[idx] = 1;
}
```

- Do we have a buffer overflow?

Example 9: Branch

```
1  #include "stdbool.h"
2  int main(int argc) {
3    int buf[10];
4    int *loc = malloc(sizeof(int));
5    int i = argc % 10;
6    if (argc == 0) {
7      *loc = i;
8    } else {
9      *loc = ++i;
10   }
11   int idx = *loc;
12   buf[idx] = 1;
13 }
```

- Do we have a buffer overflow?
- Yes, at Line 12.
- The value of the index variable `idx` can be 10, which exceeds the size 10 of the buffer `buf`.

Example 10 : Branch

```
1  #include "stdbool.h"
2  #include <stdlib.h>
3  int main(int argc) {
4    int buf[10];
5    int *loc = malloc(sizeof(int));
6    int i = argc % 10;
7    if (argc == 0) {
8      *loc = i;
9    } else {
10     *loc = ++i;
11   }
12   int idx = *loc;
13   if (idx >= 0 && idx < 10) {
14     buf[idx] = 1;
15   }
16   free(loc);
17   return 0;
18 }
```

- Do we have a buffer overflow?

Example 10 : Branch

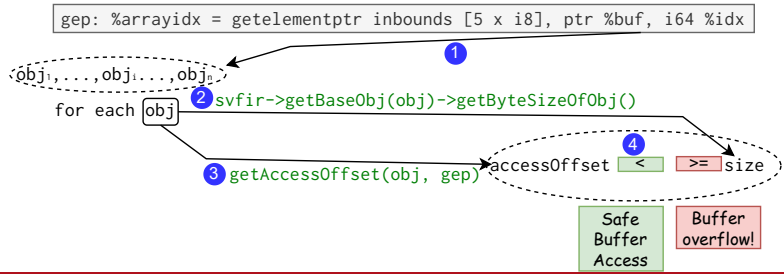
```c
#include "stdbool.h"
#include <stdlib.h>
int main(int argc) {
  int buf[10];
  int *loc = malloc(sizeof(int));
  int i = argc % 10;
  if (argc == 0) {
    *loc = i;
  } else {
    *loc = ++i;
  }
  int idx = *loc;
  if (idx >= 0 && idx < 10) {
    buf[idx] = 1;
  }
  free(loc);
  return 0;
}
```

- Do we have a buffer overflow?
- No
- The index variable `idx` is checked to ensure it is within the valid range [0, 9] before accessing `buf`.

How to Detect Buffer Overflow?

Given a buffer access `r = buf[idx]`, let's check whether there is a buffer overflow:

1. We find the memory objects (addresses) pointed by `buf`.
   - For each object `obj`:
     2. Find the byte size of `obj`, denoted as `size = bytesize(obj)`.
     3. Calculate access byte offset of `obj` considering both `idx` and its nested offset if `obj` is a sub-object of a memory allocation, via `accessOffset = accessByteOffset(obj, idx)`.
     4. Check `accessOffset` $<$ `size`. If not hold, report a potential buffer overflow. Note that abstract interpretation is an over-approximation technique and can produce false alarms.



Algorithm for Buffer Overflow Detection on SVFIR

Algorithm 1: Buffer Overflow Detection for GEPSTMT

```
1  Function bufOverflowDetection(gep):
2      as = getAbsStateFromTrace(gep→getICFGNode());
3      lhs = gep→getLHSVarID();
4      rhs = gep→getRHSVarID();
5      updateGepObjOffsetFromBase(as[lhs].getAddrs(), as[rhs].getAddrs(), as.getByteOffset(gep))
6      objAddrs = obtain the memory addresses of rhs ❶
7      for objAddr ∈ objAddrs do
8          obj = AEState :: getInternalID(objAddr);
9          size = obtain the byte size of the base object; ❷
10         accessOffset = obtain the access offset given the field/array index; ❸
11         if check if the upper bound of accessOffset is >= object size ❹ then
12             reportBufOverflow(gep→getICFGNode());
```

Handle External API `memcpy-like` (`mem_insert` and `str_insert`)?

Given a call to `mem_insert(buf:arg0, data:arg1, position:arg2, dataSize:arg3)`, the goal is to detect whether writing `size` bytes into `buf` at offset `position` overflows the buffer.

1. Get the abstract state at the callsite, and extract variable IDs for `buf`, `position`, and `dataSize`.
2. Resolve the memory (object) addresses pointed to by `buf`.
3. For each obj pointed by buf:
   - Obtain its allocated byte size: `objSize = bytesize(obj)`.
   - Compute the byte offset of this write: `accessOffset = position + size`.
4. Check whether upper bound of `accessOffset > objSize`. If so, report a possible buffer overflow.
5. Otherwise, update abstract state by performing a memory copy into the buffer using `utils->handleMemcpy`.

Handle External API `memcpy-like` (`mem_insert` and `str_insert`)?

Given a call to `mem_insert(buf:arg0, data:arg1, position:arg2, dataSize:arg3)`, the goal is to detect whether writing `size` bytes into `buf` at offset `position` overflows the buffer.

1. Get the abstract state at the callsite, and extract variable IDs for `buf`, `position`, and `dataSize`.
2. Resolve the memory (object) addresses pointed to by `buf`.
3. For each obj pointed by buf:
   - Obtain its allocated byte size: `objSize = bytesize(obj)`.
   - Compute the byte offset of this write: `accessOffset = position + size`.
4. Check whether upper bound of `accessOffset > objSize`. If so, report a possible buffer overflow.
5. Otherwise, update abstract state by performing a memory copy into the buffer using `utils->handleMemcpy`.

Note: For `str_insert`(buf:arg0, data:arg1, position:arg2), `dataSize` can be obtained by `utils->getStrlen(as, arg1)`, the string data argument and current abstract state.

`mem_insert` and `str_insert` are similar to modeling strcpy(dst, src) and memcpy(dst, src, size) in C stdlib.

Handling External Call `memcpy-like` APIs

Algorithm 2: Update Abstract State for External Call `mem_insert` `str_insert`

```
1  Function updateStateOnExtCall(extCallNode):
2      funcName = extCallNode → getCalledFunction() → getName();
3      if funcName == "mem_insert" then
4          as = retrieve post abstract state for extCallNode (1) ;
5          bufferID = extCallNode → getArgument(0) → getId();
6          positionID = extCallNode → getArgument(2) → getId();;
7          dataSizeID = extCallNode → getArgument(3) → getId(); (2) ;
8          for addr ∈ iterate over every addr of as[buffer_id] do
9              objID = retrieve the objID from virtual addr;
10             objSize = retrieve byte size of the BaseObject given objID;
11             accessOffset = calculate accessOffset by adding position and dataSize (3);
12             if check if accessOffset′s upper bound exceeds objSize (4) then
13                 reportBufOverflow(extCallNode);
14             else
15                 utils → handleMemcpy(as, dst_buffer, src_data, dataSize, position) (5)
16
17     else if funcName == "str_insert" then
18         // Similar to ‘mem_insert‘ but differs in retrieving dataSize via utils->getStrlen(as,
             extCallNode->getArgument(1))
```

Important APIs for Assignment 3

Class	API	Description
`AbstractExecution`	`getAbsStateFromTrace(node)`	Returns the abstract state immediately after a given ICFGNode
`AEState`	`as.getIDFromAddr(addr)`	Returns the internal SVFVar ID of a given address
	`as.loadValue(varId)`	Loads the abstract value of the given variable ID
	`as.storeValue(varId, val)`	Stores the abstract value at the given variable ID
	`as.getByteOffset(gep)`	Returns the byte offset of the GEP statement
	`as.getElementIndex(gep)`	Returns the element index of the GEP statement
	`as.widening(as′)`	Return a state after widening two given states
	`as.narrowing(as′)`	Return a state after narrowing two given states
`AbstractValue`	`getAddrs()`	Returns the address values in the abstract value
	`getInterval()`	Returns the interval values in the abstract value
`IntervalValue`	`lb()`	Returns the lower bound of the interval
	`ub()`	Returns the upper bound of the interval
`AbsExtAPI`	`handleMemcpy(as, dst, src, len, start_idx)`	Simulates a memcpy operation in the abstract state as: copies len bytes from the source variable src to the destination variable dst, starting at offset start_idx.
`BaseObjVar`	`getByteSizeOfObj()`	Get the byte size of this base object
`Options`	`WidenDelay()`	Returns the value of the widen delay option

*`https://github.com/SVF-tools/Software-Security-Analysis/wiki/AE-APIs#assignment-3`

Handling LoadStmt, StoreStmt and GepStmt

Algorithm 3: Abstract Execution Algorithm for LoadStmt

```
1 Function updateStateOnLoad(load):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Load the value from RHS via as.loadValue(rhs)
      and assign it to LHS;
5 Function AEState :: loadValue(varId):
6     AbstractValue res;
7     for addr : (*this)[varId].getAddrs() do
8         res.join_with(load(addr));   //join values of all objects
9     return res;
```

Algorithm 4: Abstract Execution Algorithm for StoreStmt

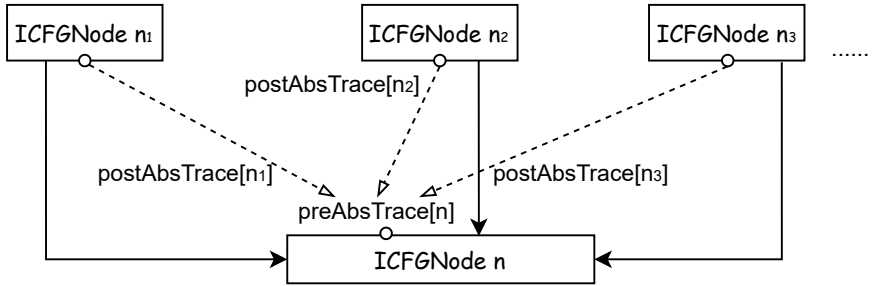
```
1 Function updateStateOnStore(store):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Store RHS value to LHS via as.storeValue;
5 Function AEState :: storeValue(varId, val):
6     for addr : (*this)[varId].getAddrs() do
7         store(addr, val);
```

Algorithm 5: Abstract Execution Algorithm for GepStmt

```
1 Function updateStateOnGep(gep):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Retrieve the field index or array index i given
      as.getElementIndex(gep);
5     // Retrieve the memory address value via
      as.getGepObjAddrs(rhs, i) and assign it to LHS
```

Merge Abstract State From Predecessors

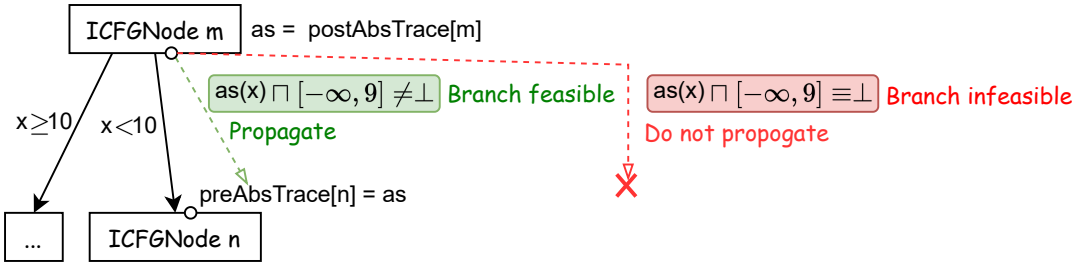
Unconditional Branch



$$preAbsTrace[n] = postAbsTrace[n_1] \sqcup postAbsTrace[n_2] \sqcup postAbsTrace[n_3] \sqcup \ldots$$

Merge Abstract State From Predecessors

Conditional Branch



Step-by-Step: A Branch Example

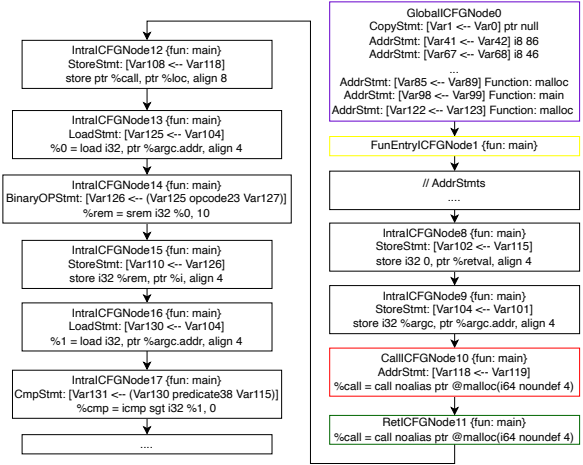
```c
#include "stdbool.h"
int main(int argc) {
    int buf[10];
    int *loc = malloc();
    int i = argc % 10;
    if (argc > 0) {
        *loc = i;
    } else {
        *loc = ++i;
    }
    int idx = *loc;
    buf[idx] = 1;
}
```

```
define dso_local i32 @main(i32 noundef %argc) #0 {
entry:
  %retval = alloca i32, align 4
  %argc.addr = alloca i32, align 4
  %buf = alloca [10 x i32], align 4
  %loc = alloca ptr, align 8
  %i = alloca i32, align 4
  %idx = alloca i32, align 4
  store i32 0, ptr %retval, align 4
  store i32 %argc, ptr %argc.addr, align 4
  %call = call noalias ptr @malloc(i64 noundef 4) #2
  store ptr %call, ptr %loc, align 8
  %0 = load i32, ptr %argc.addr, align 4
  %rem = srem i32 %0, 10
  store i32 %rem, ptr %i, align 4
  %1 = load i32, ptr %argc.addr, align 4
  %cmp = icmp sgt i32 %1, 0
  br i1 %cmp, label %if.then, label %if.else
```

```
if.then:                                          ; preds = %entry
  %2 = load i32, ptr %i, align 4
  %3 = load ptr, ptr %loc, align 8
  store i32 %2, ptr %3, align 4
  br label %if.end

if.else:                                          ; preds = %entry
  %4 = load i32, ptr %i, align 4
  %inc = add nsw i32 %4, 1
  store i32 %inc, ptr %i, align 4
  %5 = load ptr, ptr %loc, align 8
  store i32 %inc, ptr %5, align 4
  br label %if.end

if.end:                                           ; preds = %if.else, %if.then
  %6 = load ptr, ptr %loc, align 8
  %7 = load i32, ptr %6, align 4
  store i32 %7, ptr %idx, align 4
  %8 = load i32, ptr %idx, align 4
  %idxprom = sext i32 %8 to i64
  %arrayidx = getelementptr inbounds [10 x i32], ptr %buf, i64 0, i64 %idxprom
  store i32 1, ptr %arrayidx, align 4
  %9 = load i32, ptr %retval, align 4
  ret i32 %9
}
```

LLVM IR

Step-by-Step: A Branch Example



Algorithm 6: Abstract execution guided by WTO

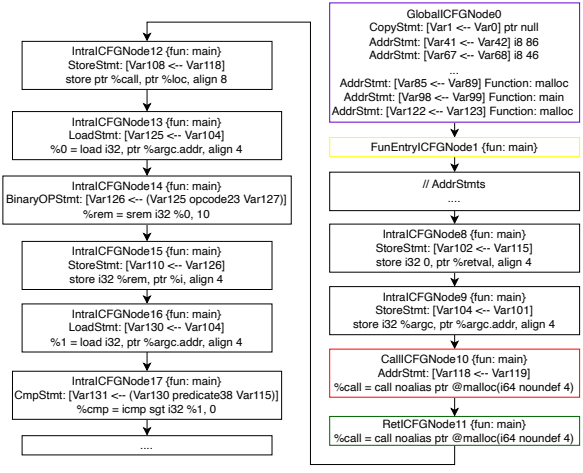
```
1 Function handleStatement(ℓ):
2     tmpAS := preAbsTrace[ℓ];
3     if ℓ is ConsStmt or AddrStmt then
4         updateStateOnAddr(ℓ);
5     else if ℓ is CopyStmt then
6         updateStateOnCopy(ℓ);
7     ...;
```

postAbsTrace[*ICFGNode17*].*varToAbsVal* :

SVFVar	AbstractValue
Var0	$\{0x7f00\}$
Var1	$\{0x7f00\}$
Var104	$0x7f000069$
Var101	$[-\infty, +\infty]$
Var125	$[-\infty, +\infty]$
Var126	$[-9, +9]$
Var130	$[-\infty, +\infty]$

Program input argument `Var101` is set to be $\top$.
Both `Var125` and `Var130` are `argc` loaded from memory.
`Var126` is variable `i`, which is [-9,9] as `i = argc mod 10`.

Step-by-Step: A Branch Example



Algorithm 7: Abstract execution guided by WTO

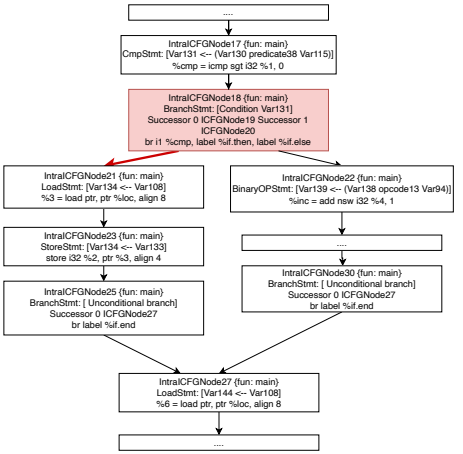
```
1 Function handleStatement(ℓ):
2     tmpAS := preAbsTrace[ℓ];
3     if ℓ is ConsStmt or AddrStmt then
4         updateStateOnAddr(ℓ);
5     else if ℓ is CopyStmt then
6         updateStateOnCopy(ℓ);
7     ...;
```

postAbsTrace[*ICFGNode17*].*varToAbsVal* :

SVFVar	AbstractValue
Var0	$\{0x7f00\}$
Var1	$\{0x7f00\}$
Var104	$0x7f000069$
Var101	$[-\infty, +\infty]$
Var125	$[-\infty, +\infty]$
Var126	$[-9, +9]$
Var130	$[-\infty, +\infty]$
Var131	$[-\infty, +\infty]$

`Var131` is the boolean branch condition.

Step-by-Step: A Branch Example



Algorithm 8: Whether Branch is Feasible

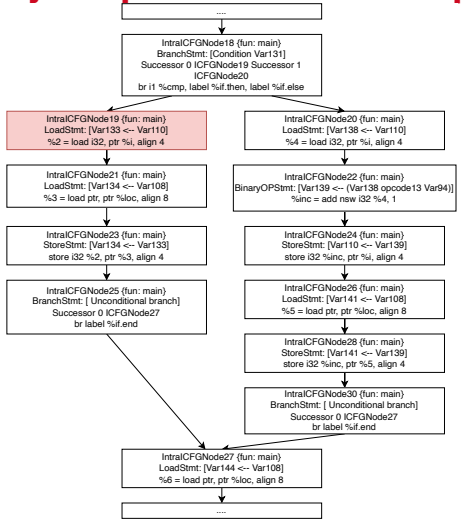
```
1  Function isBranchFeasible(intraEdge, as):
2      cond = intraEdge→getCondition();
3      cmpID = svfir→getValueNode(cond);
4      cmpVar = svfir→getGNode(cmpID);
5      if cmpVar→getInEdges().empty() then
6          return isSwitchBranchFeasible(cmpVar, intraEdge→getSuccessorCondValue(), as)
7      else
8          cmpVarInStmt = *cmpVar→getInEdges().begin();
9          if cmpStmt = SVFUtil :: dyn_cast < CmpStmt > (cmpVarInStmt) then
10             return isCmpBranchFeasible(cmpStmt, intraEdge→getSuccessorCondValue(), as)
11         else
12             return isSwitchBranchFeasible(cmpVar, intraEdge→getSuccessorCondValue(), as)
```

preAbsTrace[*ICFGNode19*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var130	$[1, +\infty]$
0x7f000069	$[1, +\infty]$
...	

The abstract state of `Var130` (`argc`) in the `if` branch is updated to $[-\infty, +\infty] \sqcap [1, +\infty]$

Step-by-Step: A Branch Example



Algorithm 9: Abstract Execution Algorithm for LOADSTMT

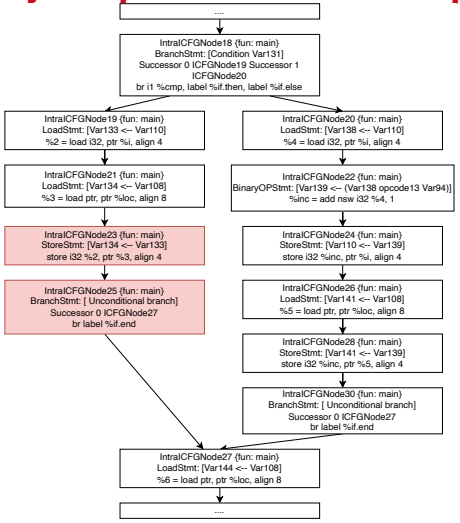
```
1 Function updateStateOnLoad(load):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Load the value from RHS via as.loadValue(rhs) and assign it to LHS;
5 Function AEState :: loadValue(varId):
6     AbstractValue res;
7     for addr : (*this)[varId].getAddrs() do
8         res.join_with(load(addr));
9     returnres;
```

postAbsTrace[*ICFGNode19*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var110	$\{0x7f00006f\}$
0x7f00006f	$[-9, 9]$
Var133	$[-9, 9]$
...	

Var133 is variable i

Step-by-Step: A Branch Example



Algorithm 10: Abstract Execution Algorithm for STORESTMT

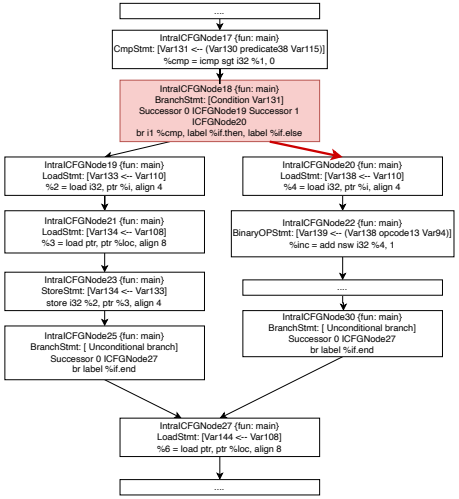
```
1 Function updateStateOnStore(store):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Store RHS value to LHS via as.storeValue;
5 Function AEState :: storeValue(varId, val):
6     for addr : (*this)[varId].getAddrs() do
7         store(addr, val);
```

postAbsTrace[*ICFGNode23*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var133	$[-9, 9]$
Var134	$\{0x7f000077\}$
0x7f000077	$[-9, 9]$
...	

Var133 is variable i
Var134 is pointer loc, which points to address 0x7f000077

Step-by-Step: A Branch Example



Algorithm 11: Whether Branch is Feasible

```
1  Function isBranchFeasible(intraEdge, as):
2      cond = intraEdge→getCondition();
3      cmpID = svfir→getValueNode(cond);
4      cmpVar = svfir→getGNode(cmpID);
5      if cmpVar→getInEdges().empty() then
6          return isSwitchBranchFeasible(cmpVar, intraEdge→getSuccessorCondValue(), as)
7      else
8          cmpVarInStmt = *cmpVar→getInEdges().begin();
9          if cmpStmt = SVFUtil :: dyn_cast < CmpStmt > (cmpVarInStmt) then
10             return isCmpBranchFeasible(cmpStmt, intraEdge→getSuccessorCondValue(), as)
11         else
12             return isSwitchBranchFeasible(cmpVar, intraEdge→getSuccessorCondValue(), as)
```

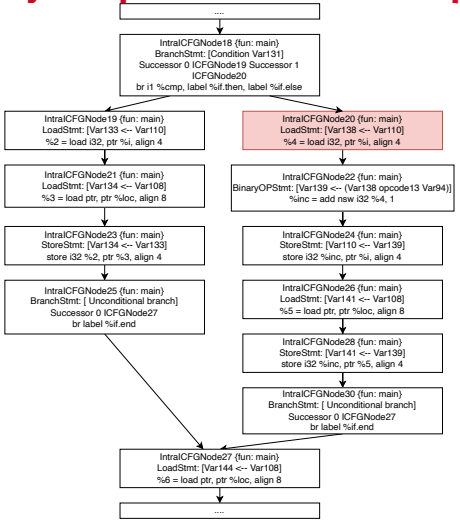
preAbsTrace[*ICFGNode20*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var130	$[\infty, 0]$
0x7f000069	$[-\infty, 0]$
...	

The abstract state of `Var130 (argc)` in the `if.else` branch is updated to $[-\infty, +\infty] \sqcap [-\infty, 0]$

`0x7f000069` is the address of `argc`

Step-by-Step: A Branch Example



Algorithm 12: Abstract Execution Algorithm for LOADSTMT

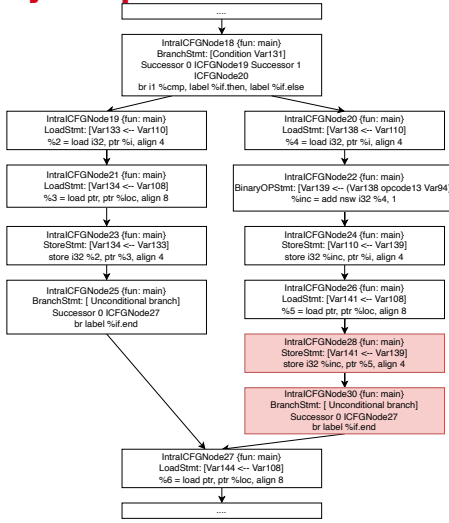
```
1 Function updateStateOnLoad(load):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Load the value from RHS via as.loadValue(rhs) and assign it to LHS;
5 Function AEState :: loadValue(varId):
6     AbstractValue res;
7     for addr : (*this)[varId].getAddrs() do
8         res.join_with(load(addr));
9     returnres;
```

postAbsTrace[*ICFGNode20*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var110	$\{0x7f00006f\}$
0x7f00006f	$[-9, 9]$
Var138	$[-9, 9]$
...	

Var138 is variable i before increment

Step-by-Step: A Branch Example



Algorithm 13: Abstract Execution Algorithm for STORESTMT

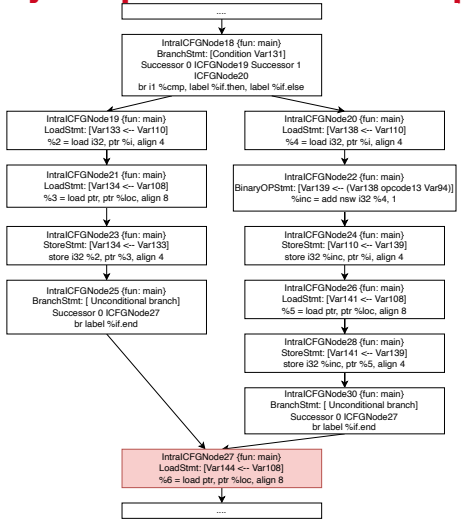
```
1 Function updateStateOnStore(store):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Store RHS value to LHS via as.storeValue;
5 Function AEState :: storeValue(varId, val):
6     for addr : (*this)[varId].getAddrs() do
7         store(addr, val);
```

postAbsTrace[*ICFGNode28*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var139	$[-8, 10]$
Var141	$\{0x7f000077\}$
0x7f000077	$[-8, 10]$
...	

`Var139` is variable `i` after increment
`Var141` is pointer `loc`, which points to address `0x7f000077`

Step-by-Step: A Branch Example

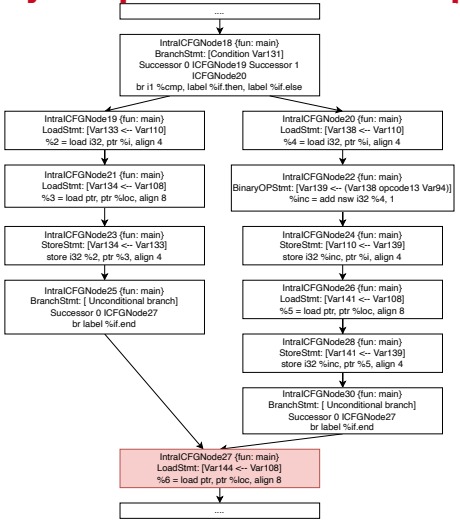


preAbsTrace[*ICFGNode27*].*varToAbsVal* :

SVFVar	AbstractValue
	...
Var108	$\{0x7f00006d\}$
0x7f00006d	$\{0x7f000077\}$
0x7f000077	$[-9, 10]$
	...

Address `0x7f000077` is pointed by pointer `loc`, its abstract value is $[-9, 10]$ formed by joining/merging $[-9, 9]$ (from ICFGNode 25) and $[-8, 10]$ (from ICFGNode 30)

Step-by-Step: A Branch Example



Algorithm 14: Abstract Execution Algorithm for LOADSTMT

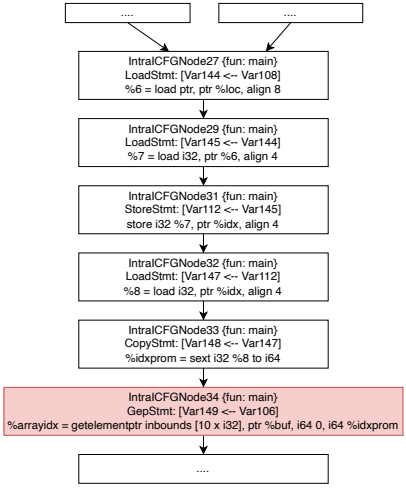
```
1 Function updateStateOnLoad(load):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Load the value from RHS via as.loadValue(rhs) and assign it to LHS;
5 Function AEState :: loadValue(varId):
6     AbstractValue res;
7     for addr : (*this)[varId].getAddrs() do
8         res.join_with(load(addr));
9     returnres;
```

postAbsTrace[*ICFGNode27*].*varToAbsVal* :

SVFVar	AbstractValue
	...
Var108	$\{0x7f00006d\}$
0x7f00006d	$\{0x7f000077\}$
Var144	$\{0x7f000077\}$
0x7f000077	$[-9, 10]$
	...

Var144 is the value of *loc, which will be used as an index idx to access array buf

Step-by-Step: A Branch Example



Algorithm 15: Abstract Execution Algorithm for GEPSTMT

```
1 Function updateStateOnGep(gep):
2     // Retrieve ICFGNode ℓ;
3     // Retrieve the abstract state as at ℓ;
4     // Retrieve the field index or array index i given as.getElementIndex(gep);
5     // Retrieve the memory address value via as.getGepObjAddrs(rhs, i) and assign
      it to LHS
```

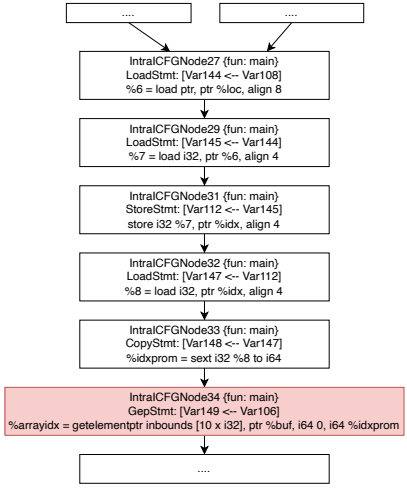
postAbsTrace[*ICFGNode27*].*varToAbsVal* :

SVFVar	AbstractValue
	...
Var106	{0x7f00006b}
Var149	{0x7f0000ea}
	...

Var106 is the base memory address of array buf

Var149 is the gep address of &buf[idx]

Step-by-Step: A Branch Example



Algorithm 16: Buffer Overflow Detection for GEPSTMT

```
1  Function bufOverflowDetection(gep):
2      as = getAbsStateFromTrace(gep→getICFGNode());
3      lhs = gep→getLHSVarID();
4      rhs = gep→getRHSVarID();
5      updateGepObjOffsetFromBase(as[lhs].getAddrs(), as[rhs].getAddrs(), as.getByteOffset(gep))
6      objAddrs = obtain the memory addresses of rhs (1)
7      for objAddr ∈ objAddrs do
8          obj = AEState :: getInternalID(objAddr);
9          size = obtain the byte size of the base object; (2)
10         accessOffset = obtain the access offset given the field/array index; (3)
11         if check if the upper bound of accessOffset is >= object size (4) then
12             reportBufOverflow(gep→getICFGNode());
```

Algorithm steps

Step	Values	Explanation
❶	*objAddrs* = {*0x7f00006b*}	from `Var106`
❷	*size* = *[10, 10]*	from `Var106`
❸	*accessOffset* = *[-9, 10]*	stored in `0x7f000077`
❹	True	overflow detected

Handling Call Site

Algorithm 17: Handle Function

```
1  Function handleFunction(fun):
2      worklist := [funEntryICFGNode] while worklist ≠ ∅ do
3          n := worklist.pop_front() ;
4          if n is a cycle head then
5              cycle := cycle_head_to_cycle[n] ;
6              handleICFGCycle(cycle); ;        // Assignment-3
7              foreach n′ ∈ getNextNodesOfCycle(cycle) do
8                  worklist.push_back(n′) ;
9          else
10             if handleICFGNode(n) == false then
11                 foreach n′ ∈ getNextNodes(n) do
12                     worklist.push_back(n′) ;
```

Algorithm 18: Abstract Execution for Function Call

```
1  Function handleCallSite(callNode):
2      callee = callNode → getCalledFunction();
3      if ... then
4          // if handle stub functions, random or external API calls
5      else if isExternalCallForAssignment(callee) then
6          updateStateOnExtCall(callNode);
7      else if callee ∈ recursiveFuns then
8          return;
9      else
10         calleeEntry = icfg → getFunEntryICFGNode(callee);
11         handleFunction(calleeEntry);
```

Step-by-Step: An Interprocedural Example

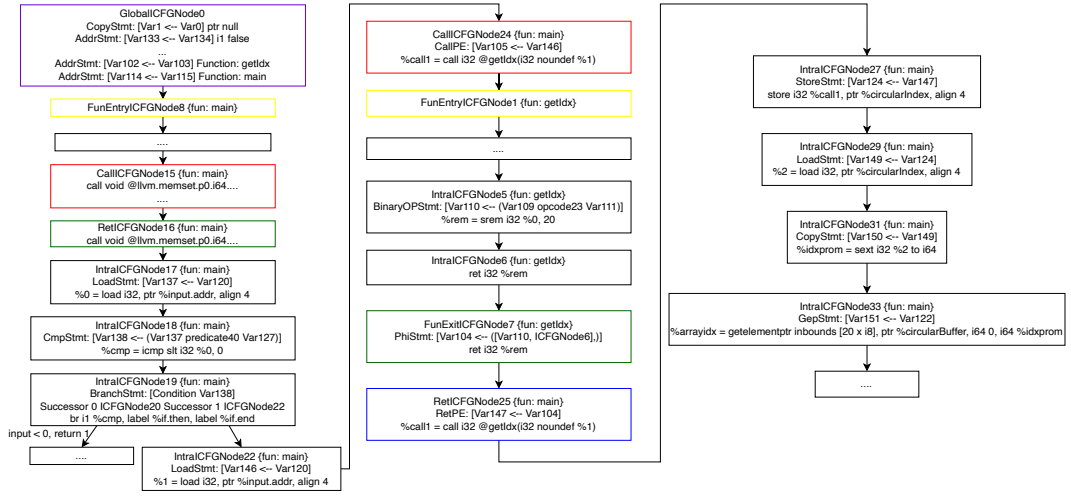
```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#define CIRC_BUF_SIZE 20
#define ERR_MSG "Error: negative index!\n"

int getIdx(int index) {
    return index % CIRC_BUF_SIZE;
}
int main(int input) {
    char circBuf[CIRC_BUF_SIZE] = {0};
    if(input < 0) {
        printf(ERR_MSG);
        return 1;
    }
    int circIdx = getIdx(input);
    circBuf[circIdx] = 'A';
    return 0;
}
```

```
define dso_local i32 @getIdx(i32 noundef %index) #0 {
entry:
  %index.addr = alloca i32, align 4
  store i32 %index, ptr %index.addr, align 4
  %0 = load i32, ptr %index.addr, align 4
  %rem = srem i32 %0, 20
  ret i32 %rem
}

define dso_local i32 @main(i32 noundef %input) #0 {
entry:
  %retval = alloca i32, align 4
  %input.addr = alloca i32, align 4
  %circularBuffer = alloca [20 x i8], align 1
  %circularIndex = alloca i32, align 4
  store i32 0, ptr %retval, align 4
  store i32 %input, ptr %input.addr, align 4
  call void @llvm.memset.p0.i64(ptr align 1 %circularBuffer,
i8 0, i64 20, i1 false)
  %0 = load i32, ptr %input.addr, align 4
  %cmp = icmp slt i32 %0, 0
  br i1 %cmp, label %if.then, label %if.end
```

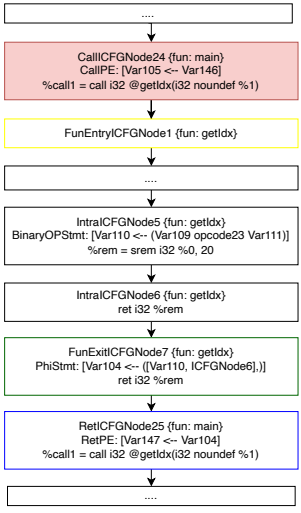
```
if.then:                                          ; preds = %entry
  %call = call i32 (ptr, ...) @printf(ptr noundef @.str)
  store i32 1, ptr %retval, align 4
  br label %return

if.end:                                           ; preds = %entry
  %1 = load i32, ptr %input.addr, align 4
  %call1 = call i32 @getIdx(i32 noundef %1)
  store i32 %call1, ptr %circularIndex, align 4
  %2 = load i32, ptr %circularIndex, align 4
  %idxprom = sext i32 %2 to i64
  %arrayidx = getelementptr inbounds [20 x i8], ptr
%circularBuffer, i64 0, i64 %idxprom
  store i8 65, ptr %arrayidx, align 1
  store i32 0, ptr %retval, align 4
  br label %return

return:                                           ; preds = %if.end, %if.then
  %3 = load i32, ptr %retval, align 4
  ret i32 %3
}
```

LLVM IR

Step-by-Step: An Interprocedural Example



Step-by-Step: An Interprocedural Example



Algorithm 19: Abstract Execution for Function Call

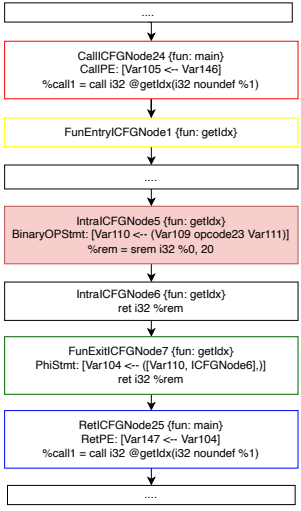
```
1  Function handleCallSite(callNode):
2      callee = callNode → getCalledFunction();
3      if ... then
4          // if handle stub functions, random or external API calls
5      else if isExternalCallForAssignment(callee) then
6          updateStateOnExtCall(callNode);
7      else if callee ∈ recursiveFuns then
8          return;
9      else
10         calleeEntry = icfg → getFunEntryICFGNode(callee);
11         handleFunction(calleeEntry);
```

postAbsTrace[*ICFGNode24*].*varToAbsVal* :

SVFVar	AbstractValue
	...
Var146	$[0, \infty]$
Var105	$[0, \infty]$
	...

The `AbstractExecution` in `Assignment-3` is **context-insensitive** and `callSiteStack` is only used to maintain call stack information for bug reporting.

Step-by-Step: An Interprocedural Example



Algorithm 20: Handle Function

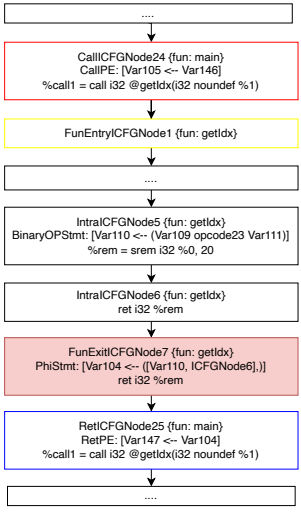
```
1  Function handleFunction(fun):
2      worklist := [funEntryICFGNode] while worklist ≠ ∅ do
3          n := worklist.pop_front() ;
4          if n is a cycle head then
5              cycle := cycle_head_to_cycle[n] ;
6              handleICFGCycle(cycle);
7              foreach n′ ∈ getNextNodesOfCycle(cycle) do
8                  worklist.push_back(n′) ;
9          else
10             if handleICFGNode(n) == false then
11                 foreach n′ ∈ getNextNodes(n) do
12                     worklist.push_back(n′) ;
```

postAbsTrace[*ICFGNode5*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var109	$[0, +\infty]$
Var110	$[0, 19]$
...	

`Var109` is variable `index`, which is $[0, +\infty]$.
`Var110` is the return value of function `getIdx`, which is [0,19] as `Var110 = index` mod 20.

Step-by-Step: An Interprocedural Example



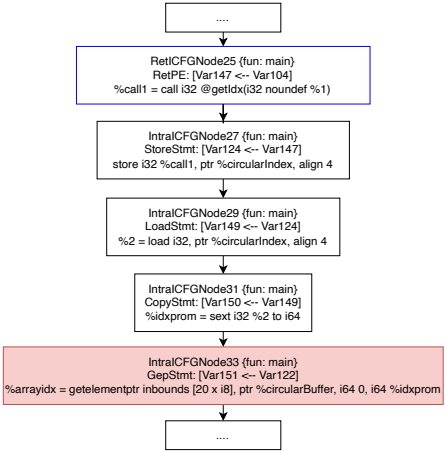
Algorithm 21: Handle Function

```
1  Function handleFunction(fun):
2      worklist := [funEntryICFGNode] while worklist ≠ ∅ do
3          n := worklist.pop_front() ;
4          if n is a cycle head then
5              cycle := cycle_head_to_cycle[n] ;
6              handleICFGCycle(cycle); foreach
                n′ ∈ getNextNodesOfCycle(cycle) do
7                  worklist.push_back(n′) ;
8          else
9              if handleICFGNode(n) == false then
10                 foreach n′ ∈ getNextNodes(n) do
11                     worklist.push_back(n′) ;
```

postAbsTrace[*ICFGNode7*].*varToAbsVal* :

SVFVar	AbstractValue
...	
Var110	[0, 19]
Var104	[0, 19]
...	

Step-by-Step: An Interprocedural Example



Algorithm 22: Buffer Overflow Detection for GEPSTMT

```
1  Function bufOverflowDetection(gep):
2      as = getAbsStateFromTrace(gep→getICFGNode());
3      lhs = gep→getLHSVarID();
4      rhs = gep→getRHSVarID();
5      updateGepObjOffsetFromBase(as[lhs].getAddrs(), as[rhs].getAddrs(), as.getByteOffset(gep))
6      objAddrs = obtain the memory addresses of rhs ❶
7      for objAddr ∈ objAddrs do
8          obj = AEState :: getInternalID(objAddr);
9          size = obtain the byte size of the base object; ❷
10         accessOffset = obtain the access offset given the field/array index; ❸
11         if check if the upper bound of accessOffset is >= object size ❹ then
12             reportBufOverflow(gep→getICFGNode());
```

Algorithm behavior

Step	Behavior
❶	*objAddrs* = {*0x7f00007b*}
❷	*size* = *[20, 20]*
❸	*accessOffset* = *[0, 19]*
❹	False, the buffer access is safe!

Final Week and How to Make the Most of This Course

- You are now able to build your own code checkers and verifiers (including information flow tracking, symbolic execution, and abstract interpretation)
- Join and contribute to SVF code analysis framework?
  - `https://github.com/SVF-tools/SVF`
- Participate in software verification competitions (SVC)
  - `https://sv-comp.sosy-lab.org/`
  - `https://docs.google.com/document/d/1bgkx5lnugrwlNzQ2MPRSd47MAkZGJfR9v2jo7oRskd0/edit`
- An honours thesis project or a research degree (MPhil or PhD)?
- Tutor and lab demonstrator next year?

Final Week and Thank You!

- Thank you for participating in the inaugural offering of this course. We hope you enjoy this journey with us!
- We would also like to thank the course administrators and lab demonstrators.