Kernel CARAT --- “KARAT”

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Brian Suchy, Peter Dinda

Outline

- CARAT --- Overview
- Kernel CARAT --- “KARAT”
  - CARAT in Nautilus
  - Compiler Mechanics
  - Runtime Mechanics
- Next Steps

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CARAT --- Overview

Replaces the **paging model** of memory management with a **software-only** abstraction

Comprised of two overarching pieces:

- Runtime --- To dynamically build a view of a program's memory
- Compiler Transforms ---
  - To inject code that calls runtime methods for building a memory map
  - To provide protection for accessing and/or referencing memory

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- Next Steps

Kernel CARAT --- “KARAT”

- The current implementation of CARAT is at **user level**
- To truly test the concept, we need to try it at **kernel level**
- This is a **non-trivial** task:
    - Need to account for complex paging systems --- CARAT works at the allocation granularity of pages
    - Applying whole-kernel compiler transformations is tricky
    - Multiple processors, context switching, etc. will cause headaches
    - Need to confirm that KARAT will not affect the memory allocation system

Outline

- CARAT --- Overview
- **Kernel CARAT --- “KARAT”**
  - **CARAT in Nautilus**
  - Compiler Mechanics
  - Runtime Mechanics
- Example
- Next Steps

KARAT: CARAT in Nautilus

- To run CARAT in Nautilus, we need to accomplish the following:
  - **Port** the CARAT **runtime** into Nautilus
  - **Port** and **run** the CARAT **compiler transforms** on all Nautilus code, injecting calls to new runtime and custom instructions into the kernel
- Nautilus has **advantages**:
  - Uses the **simplest paging** implementation
  - Nautilus **can compile** with **several compiler toolchains**, including ones with custom transformations

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    - **Compiler Mechanics**
    - Runtime Mechanics
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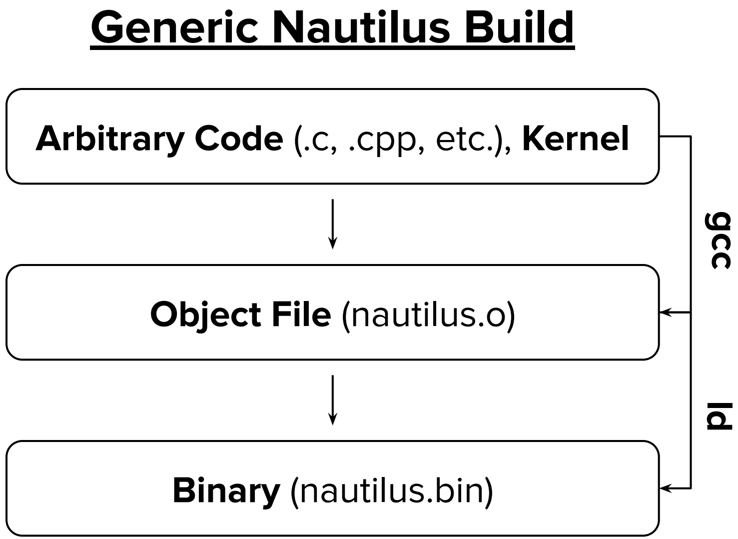
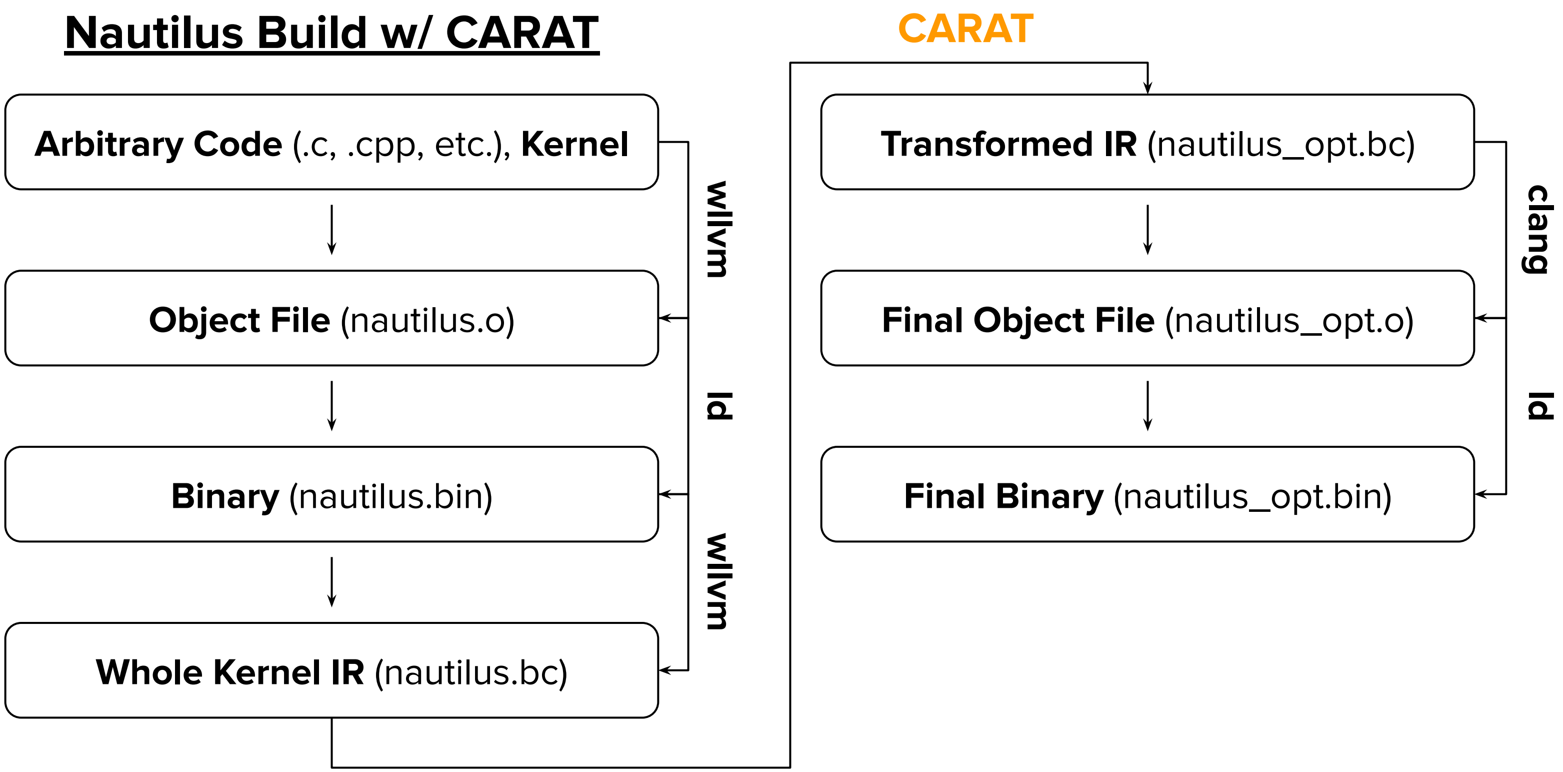
KARAT: Compiler Mechanics



KARAT: Compiler Mechanics



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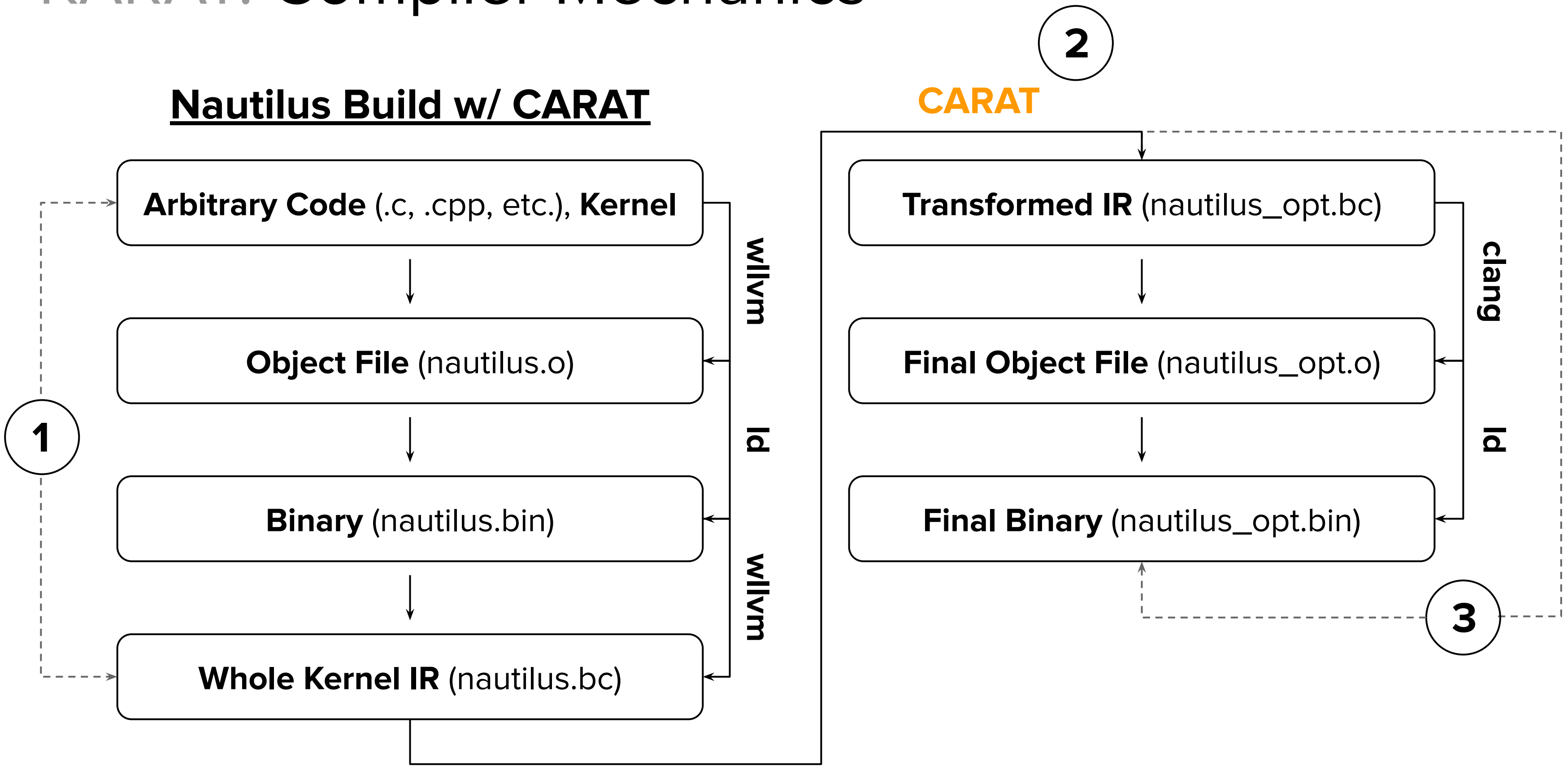

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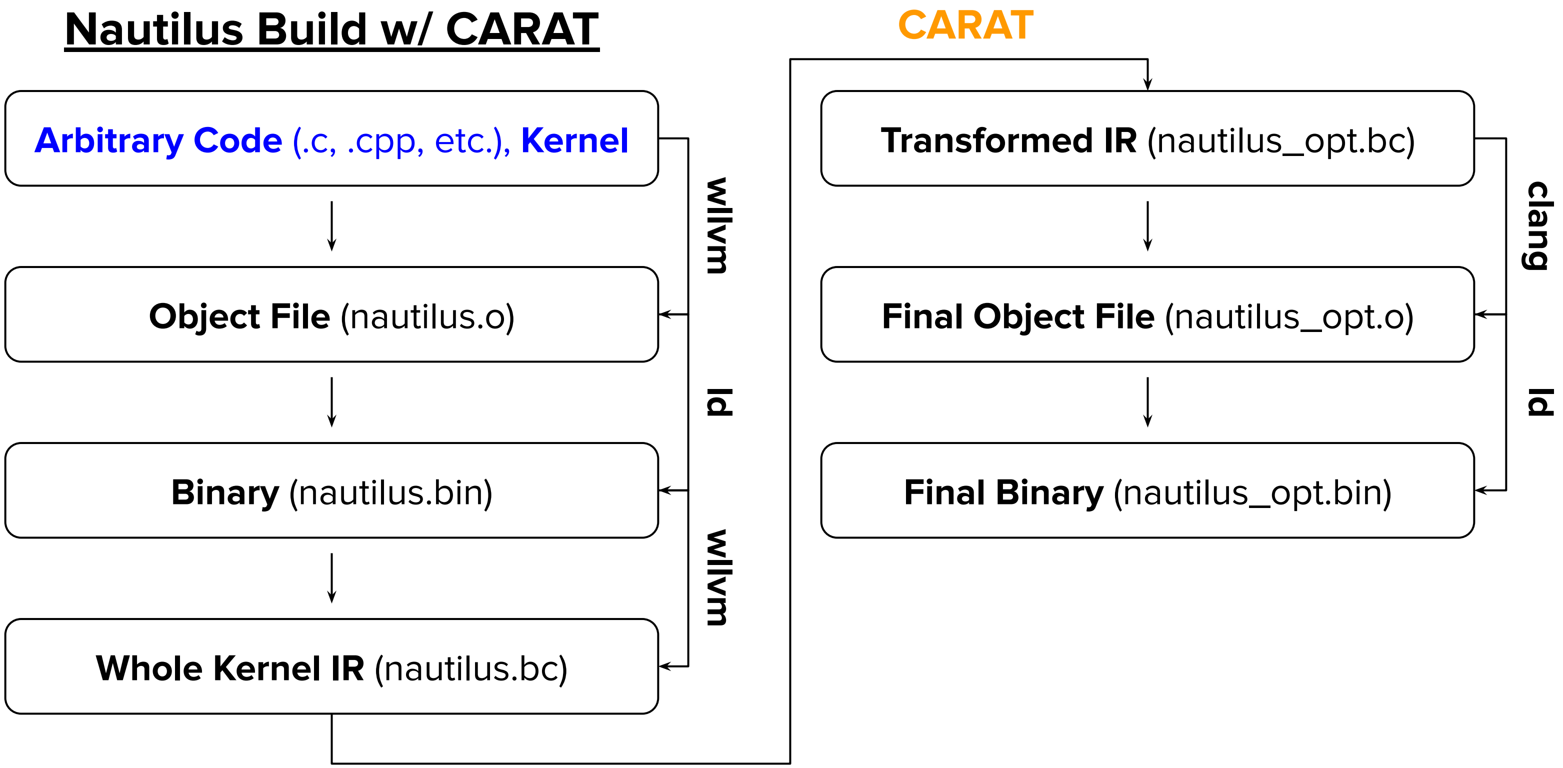


Arbitrary Code (.c, .cpp, etc.), **Kernel**

↓

. . .

CARAT Runtime

`nk_set`

`nk_map`

`nk_slist`

Arbitrary Code (.c, .cpp, etc.), **Kernel**

...

CARAT Runtime

`nk_set`

`nk_map`

`nk_slist`

- We're porting a simplified version of the CARAT runtime
- But ... porting from C++ to C is **complicated**

CARAT Runtime

`nk_set`

`nk_map`

`nk_slist`

- Nautilus does **not** include the C++ STL or many data structures
- We have to **build** the ones we need in **C**

CARAT Runtime

`nk_set`

`nk_map`

`nk_slist`

- We need sorted **maps** and sorted **sets**

CARAT Runtime

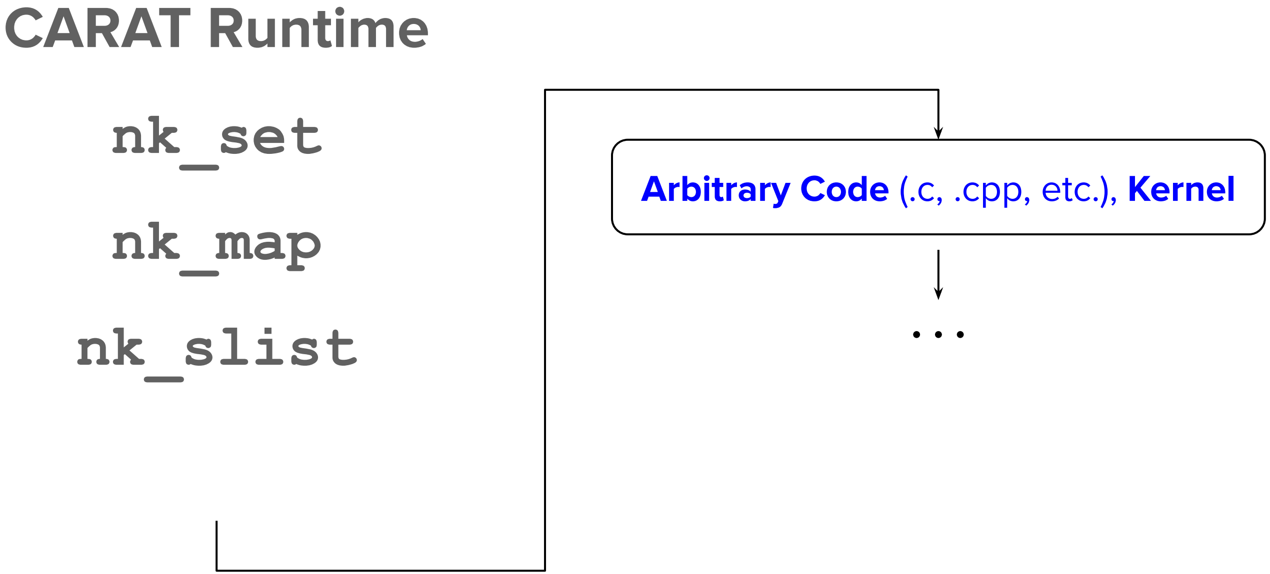
`nk_set`

`nk_map`

`nk_slist`

- We need sorted **maps** and sorted **sets**

- We're using **skiplists** as the underlying data structure to create these abstractions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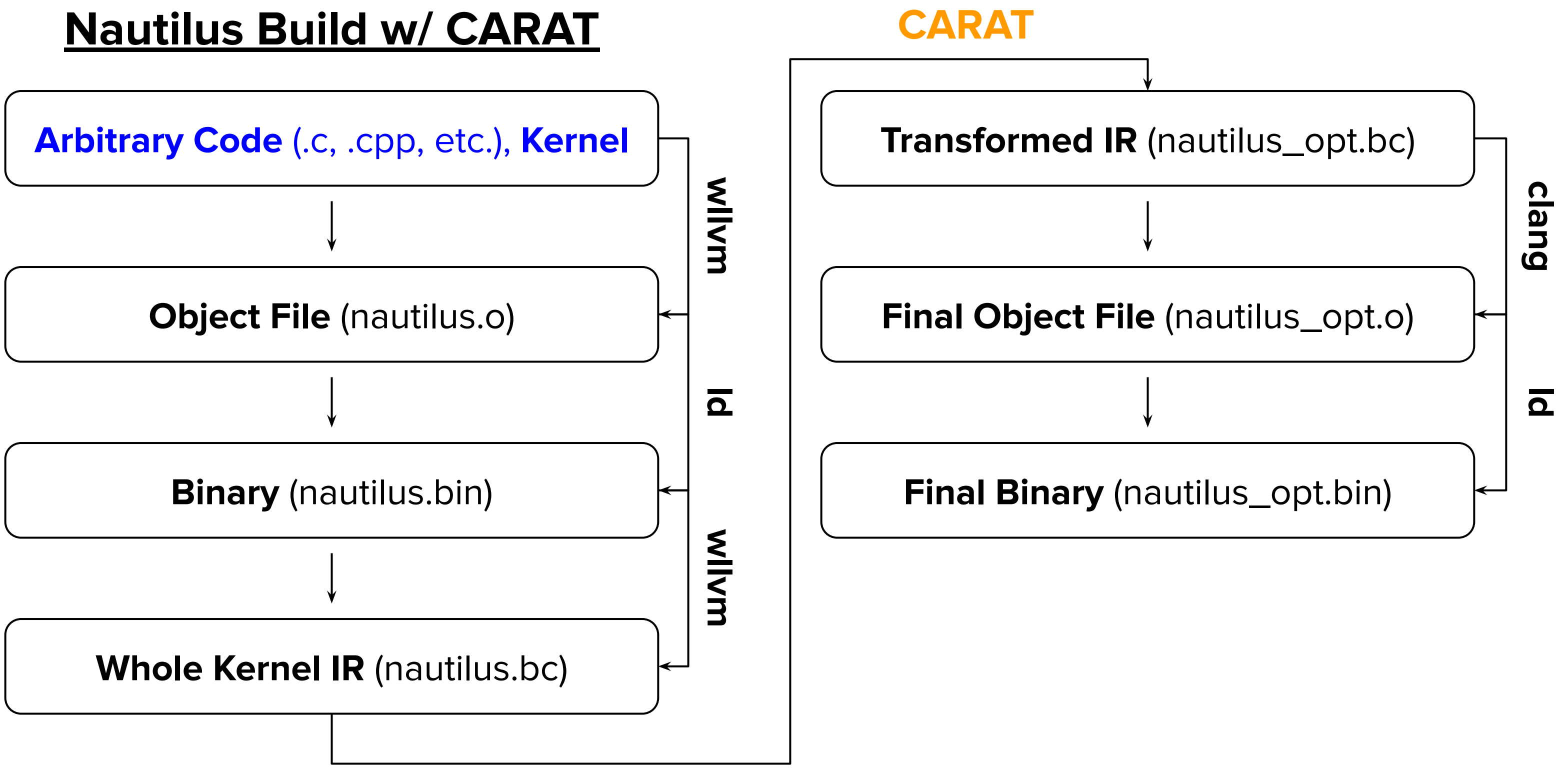
KARAT: Compiler Mechanics



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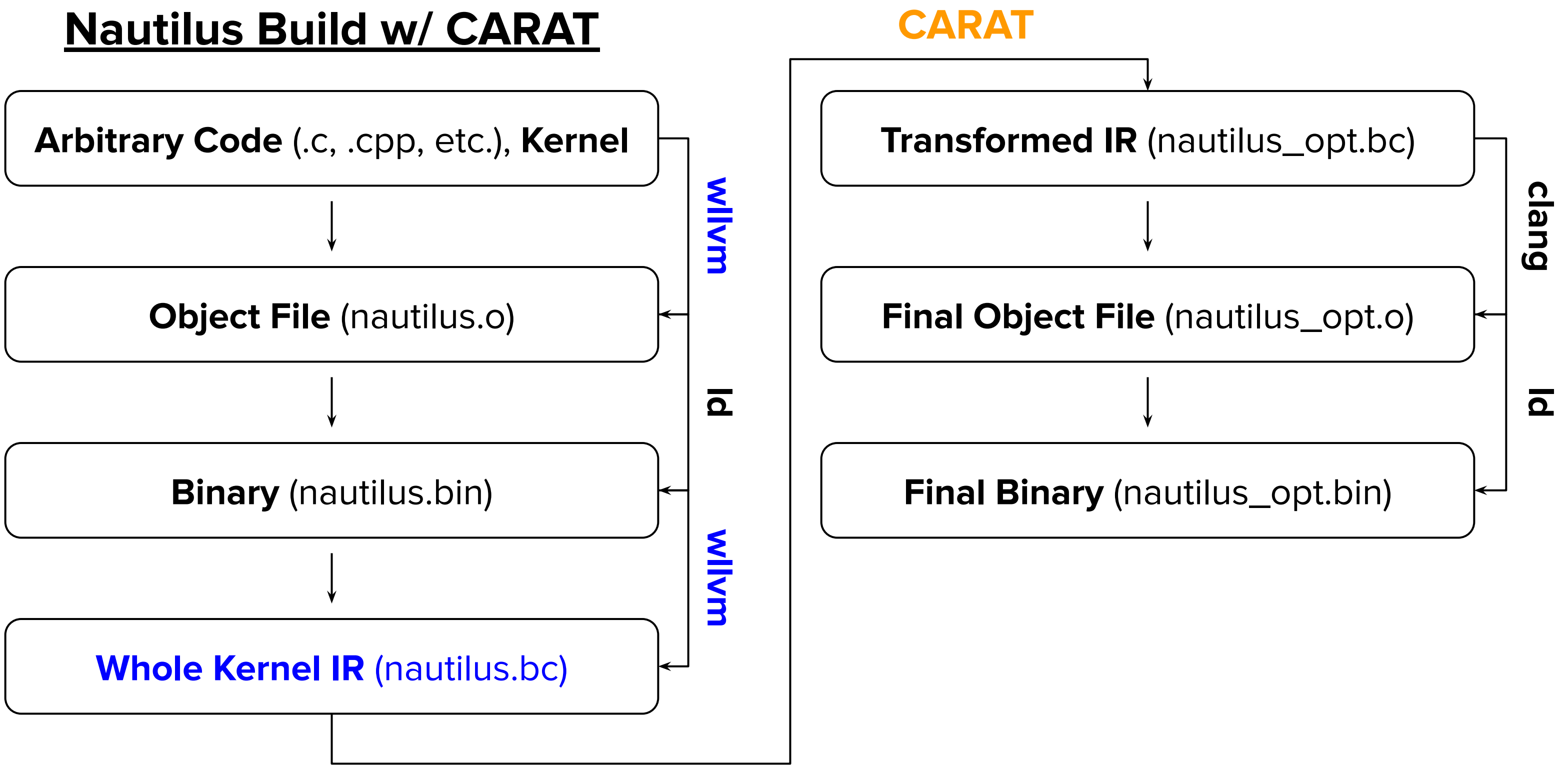
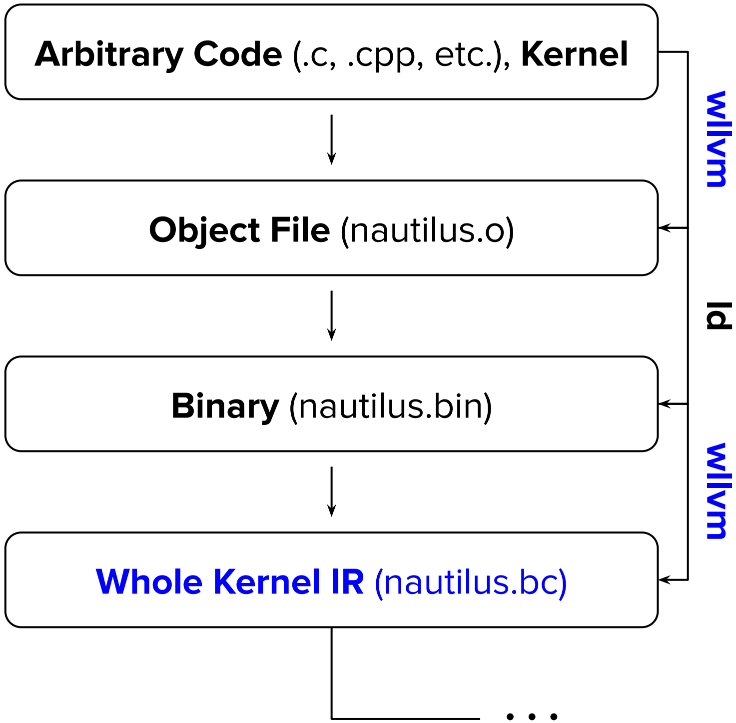
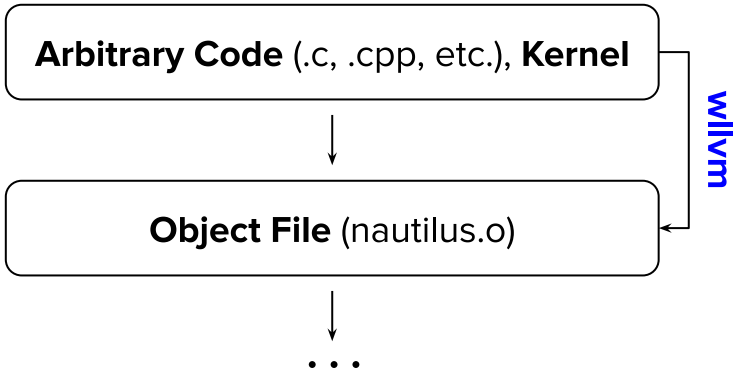



Arbitrary Code (.c, .cpp, etc.), **Kernel**
Object File (nautilus.o)
Binary (nautilus.bin)
Whole Kernel IR (nautilus.bc)
wllvm
ld
wllvm
. . .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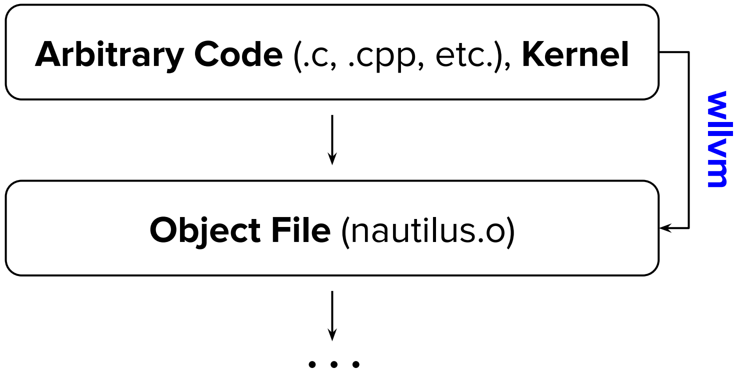
LLVM

clang

wllvm



LLVM

- LLVM is the **compiler infrastructure** we're using to build and transform Nautilus
- We're targeting the middle-end (**IR**)

LLVM

clang

wllvm

- Clang is the **front-end** that LLVM uses to compile C and C++ sources --- we usually refer to the whole compiler as “clang”

LLVM

clang

wllvm

- WLLVM, or **whole program LLVM**, is a wrapper built on top of clang that separately produces **LLVM IR** for any compiled source

LLVM

clang

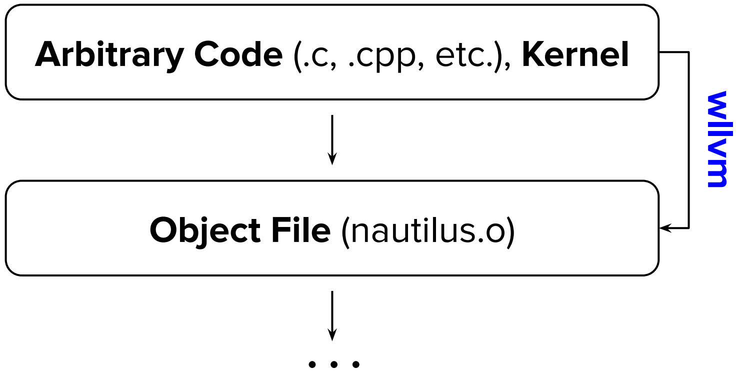
wllvm

- WLLVM uses a specialized **linker** and **IR generator** that builds and stores the IR in a specific section of the object/binary

LLVM

clang

wllvm



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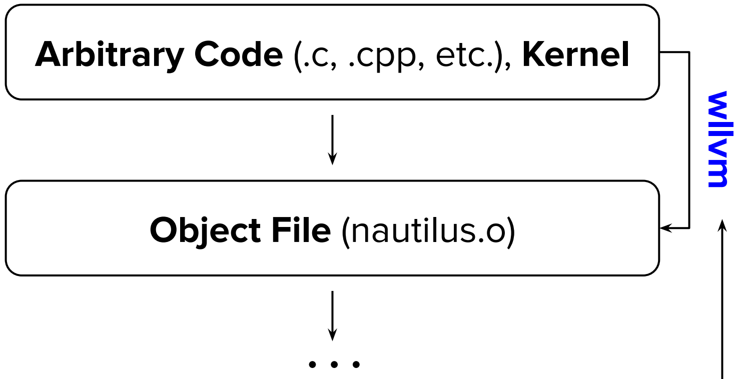
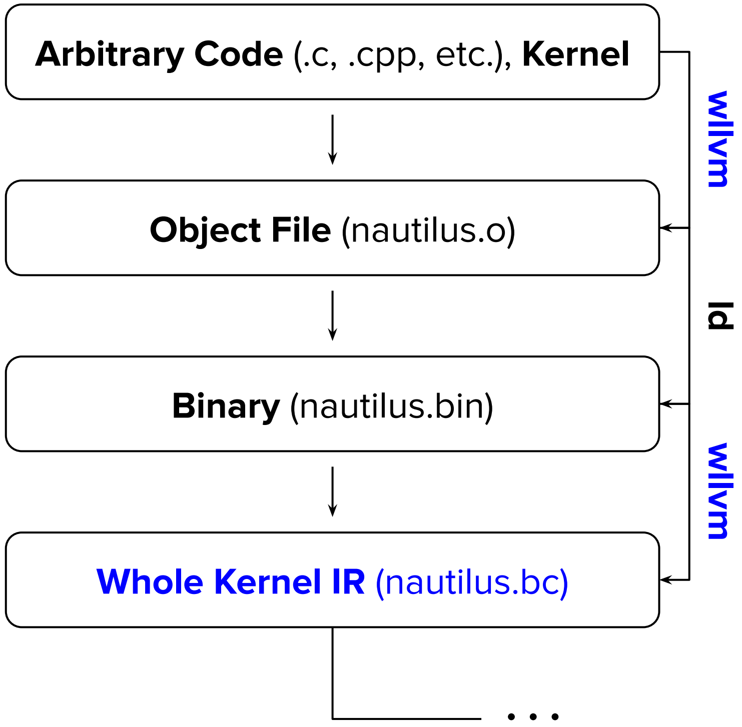


All three pieces are invoked in this step!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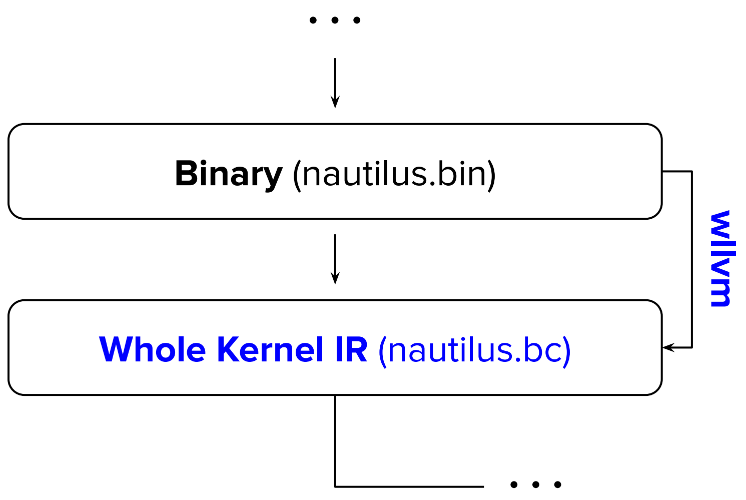

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Binary (nautilus.bin)
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Whole Kernel IR (nautilus.bc)
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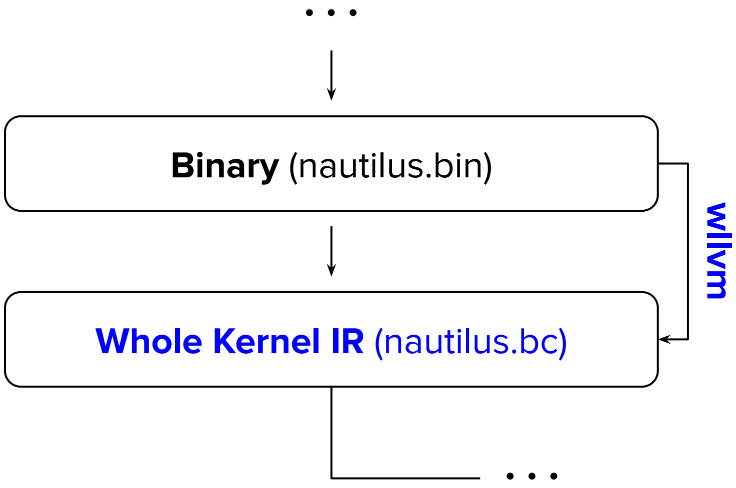
wllvm

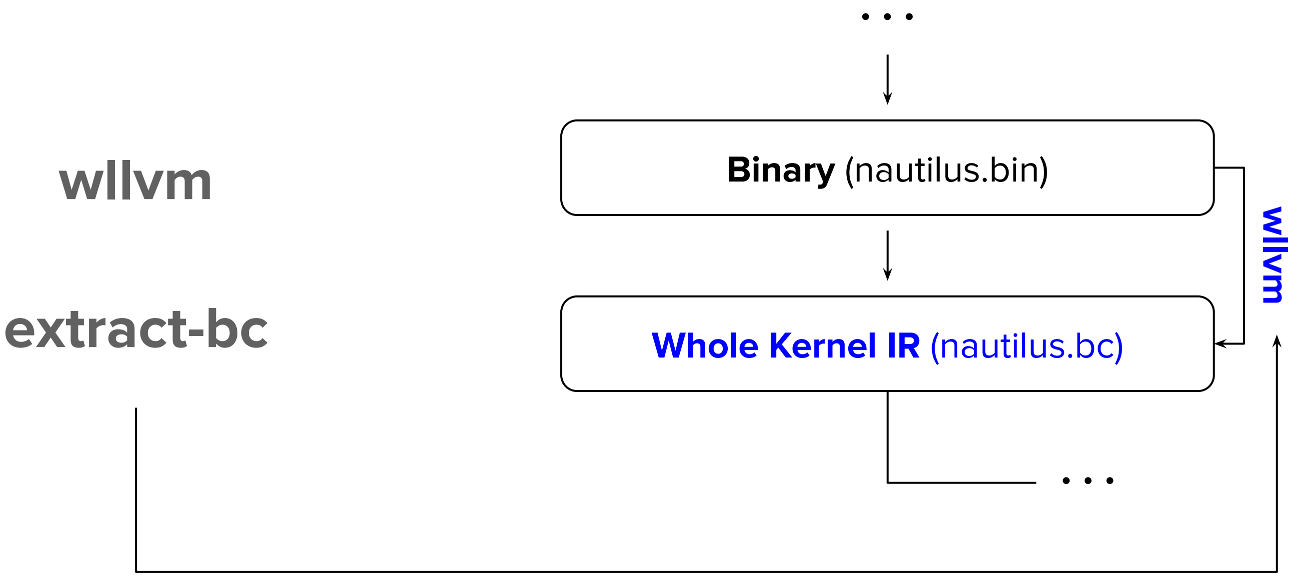
extract-bc



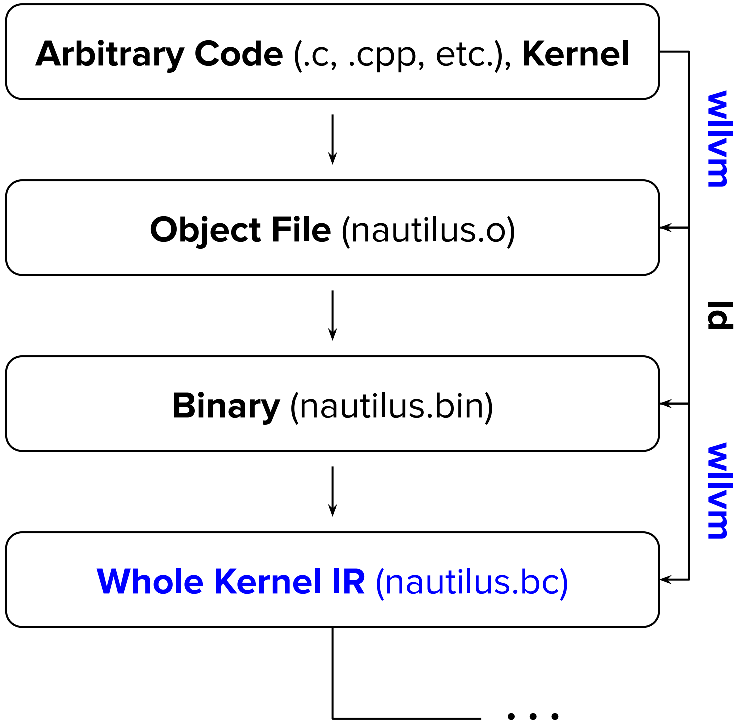
wllvm

extract-bc

- extract-bc is the feature of WLLVM that allows a user to extract **all LLVM IR** from a object/binary



extract-bc gets the **whole kernel IR** from nautilus.bin



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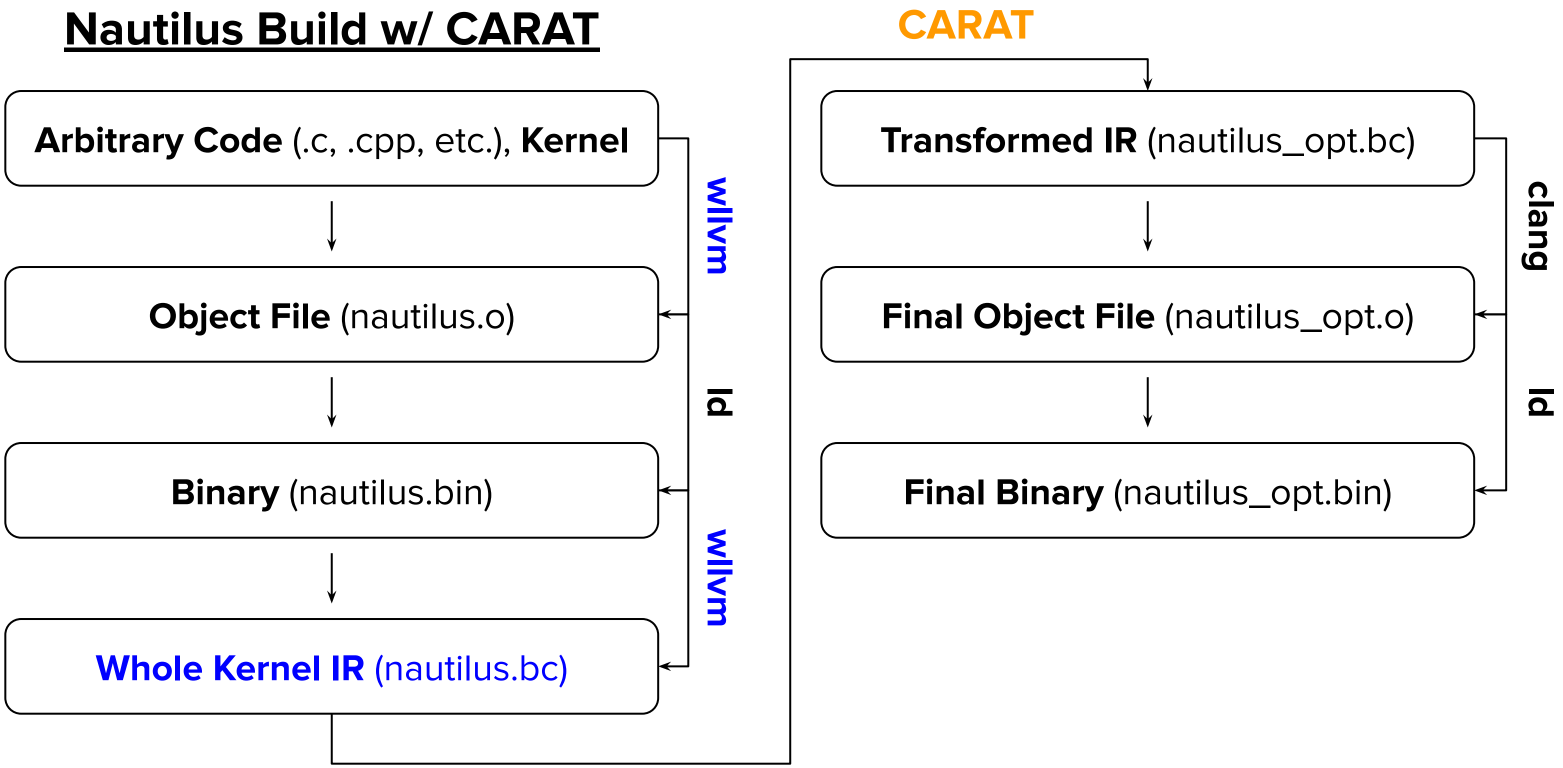
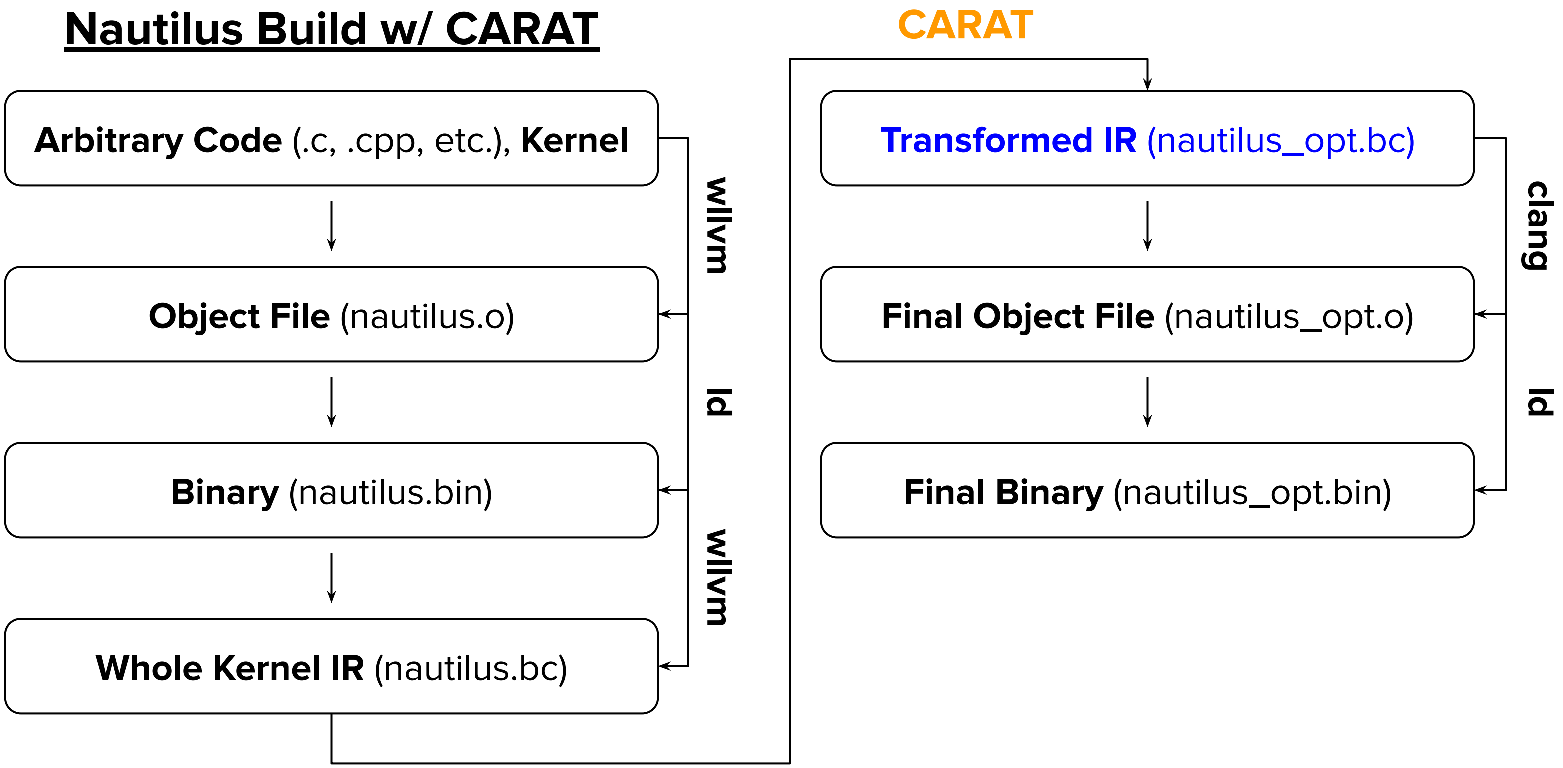
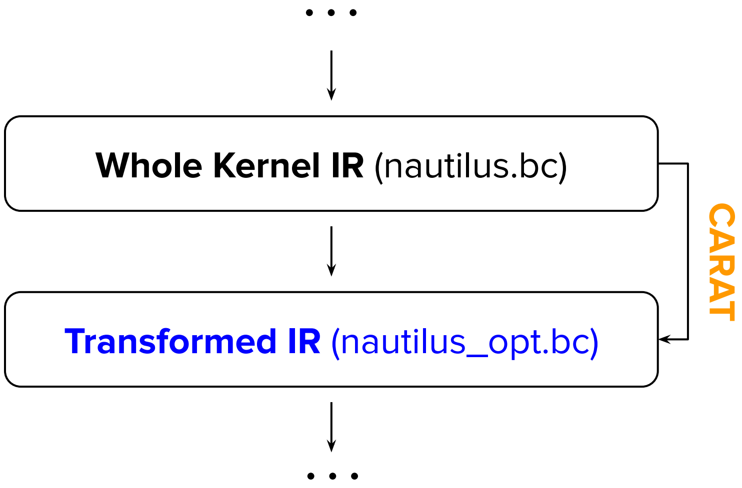
KARAT: Compiler Mechanics



KARAT: Compiler Mechanics

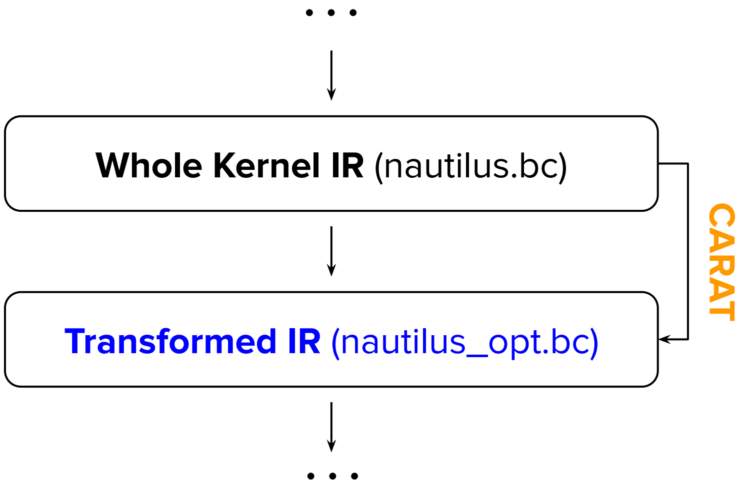



...
Whole Kernel IR (nautilus.bc)
Transformed IR (nautilus_opt.bc)
CARAT
...

Allocation Tracking

Escapes Tracking

Protections



Allocation Tracking

Escapes Tracking

Protections

- Allocation tracking is a feature in CARAT that tracks **heap memory** while the kernel is running

Allocation Tracking

Escapes Tracking

Protections

- In Nautilus, this means all calls to **`kmem_malloc`**, **`kmem_realloc`**, and **`free`** are tracked

Allocation Tracking

Escapes Tracking

Protections

- All **globals** are also tracked, since global variables are generally heap-allocated

Allocation Tracking

Escapes Tracking

Protections

- But what does **tracking** mean? All calls are succeeded with a call to the runtime that records the **pointer** and **size of the allocation** to a table

Allocation Tracking

Escapes Tracking

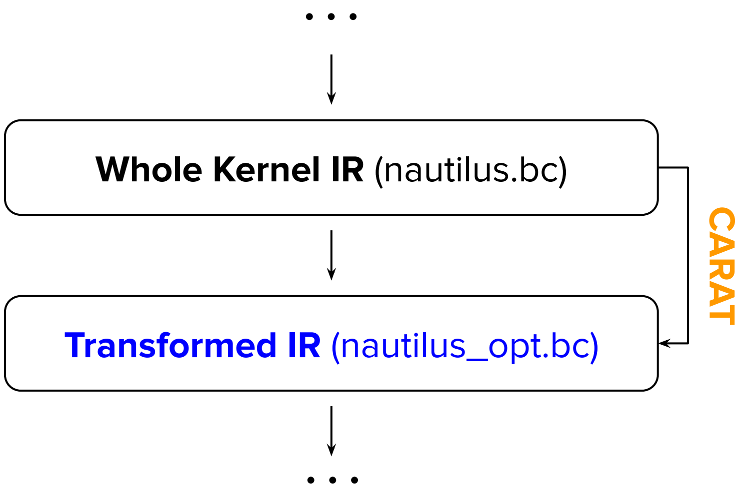
Protections

- Allocation tracking is implemented as a middle-end LLVM transform --- **injecting calls** to the runtime

Allocation Tracking

Escapes Tracking

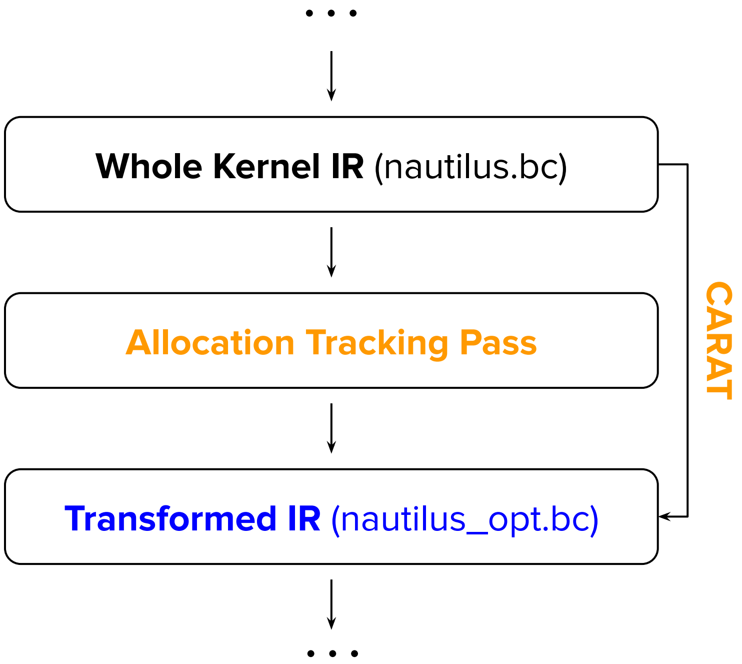
Protections



Allocation Tracking

Escapes Tracking

Protections



Allocation Tracking

Escapes Tracking

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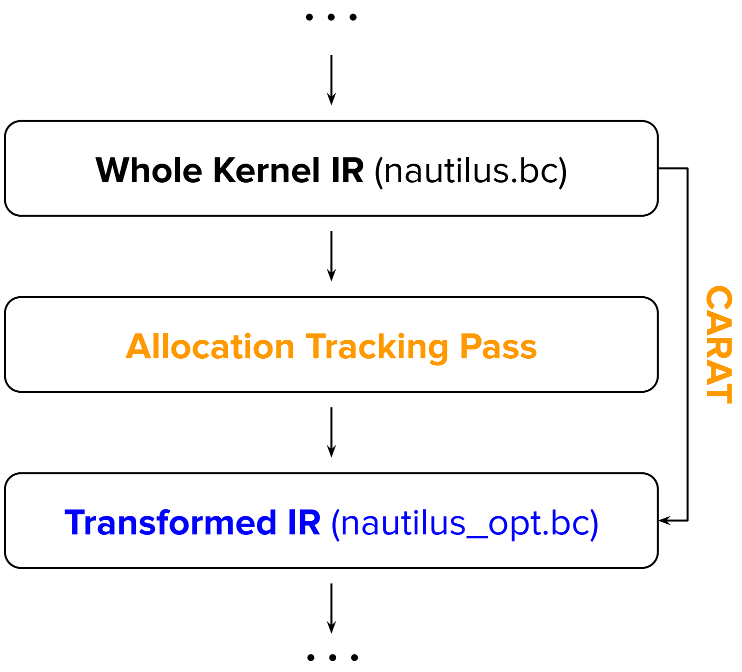


Allocation Tracking

Escapes Tracking

Protections

- Escapes tracking is a feature in CARAT that tracks all “escapes” or **references to allocated memory**

Allocation Tracking

Escapes Tracking

Protections

- Here, **tracking** applies to all **stores** of pointers
- All stores are succeeded with a call to the runtime to account for the **escaped pointer**

Allocation Tracking

Escapes Tracking

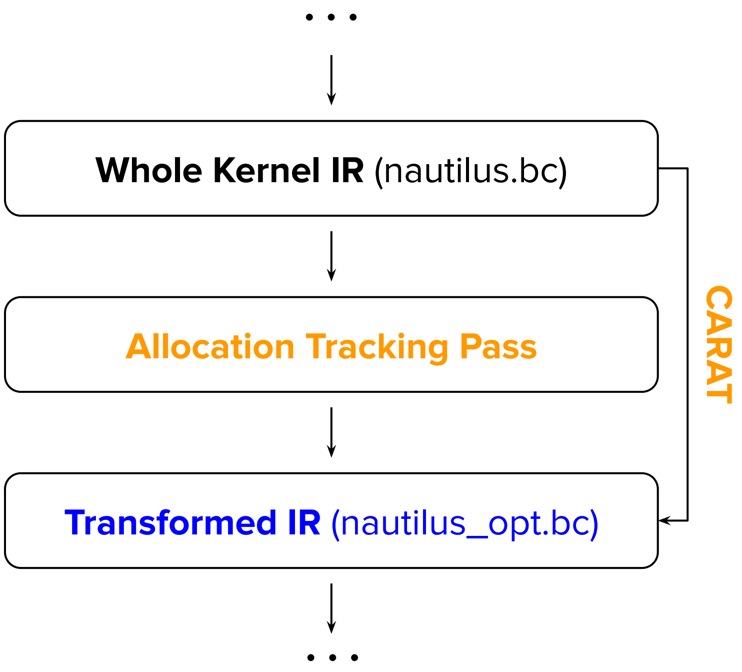
Protections

- Escapes tracking is also implemented as a middle-end LLVM transform --- **injecting calls** to the runtime

Allocation Tracking

Escapes Tracking

Protections



Allocation Tracking

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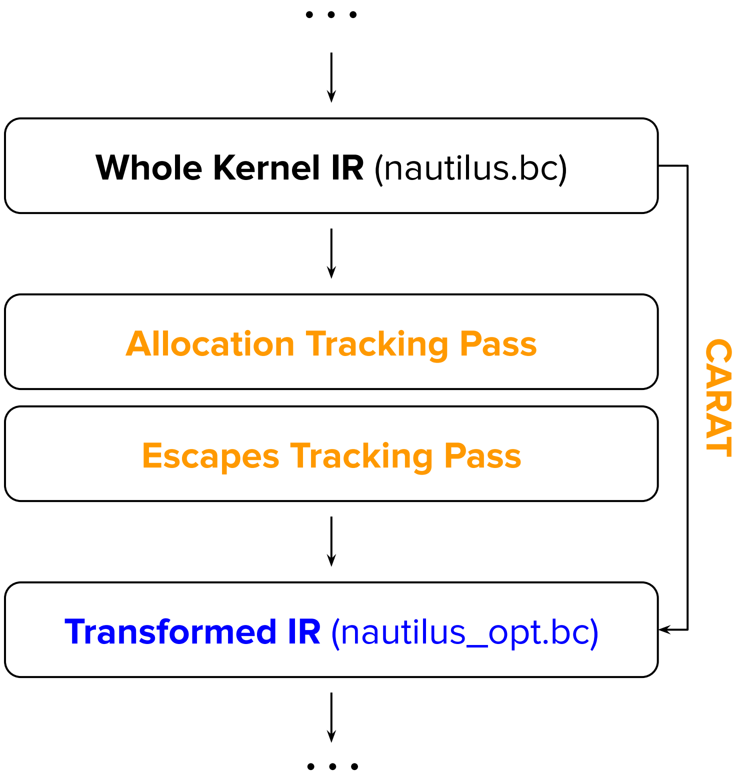
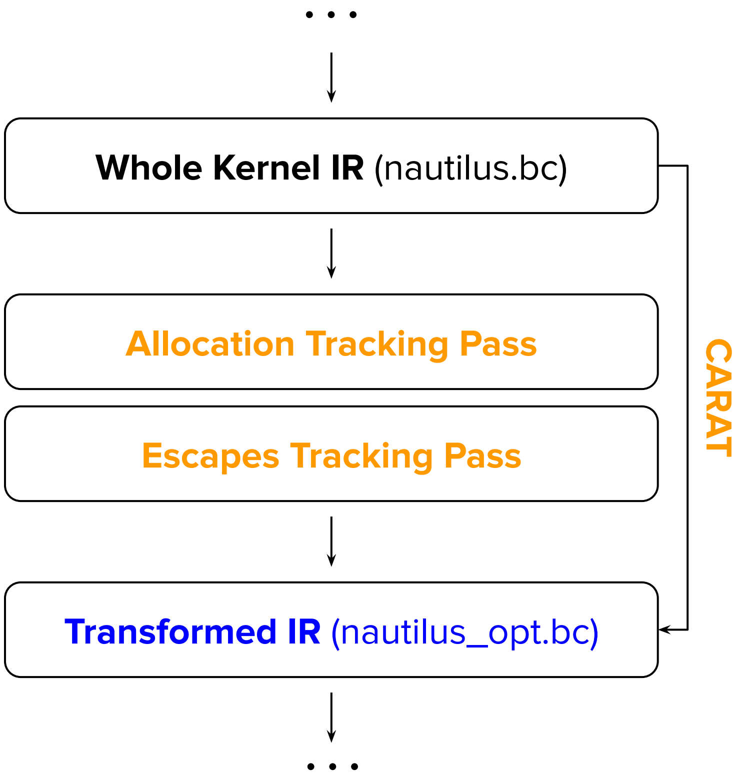


Allocation Tracking

Escapes Tracking

Protections



Allocation Tracking

Escapes Tracking

Protections

- CARAT provides protections to reads and writes --- making sure all references are **valid**

Allocation Tracking

Escapes Tracking

Protections

- **Valid** addresses in Nautilus correspond to **canonical** addresses, and depend on the address space that Nautilus is using at any given time

Allocation Tracking

Escapes Tracking

Protections

- Protections require checking **all references**
- The injected code will cause a **panic** if a reference is not valid

Allocation Tracking

Escapes Tracking

Protections

- Checking every reference is **expensive** --- CARAT employs a custom **data-flow analysis** and **loop invariant analysis** to reduce overhead

Allocation Tracking

Escapes Tracking

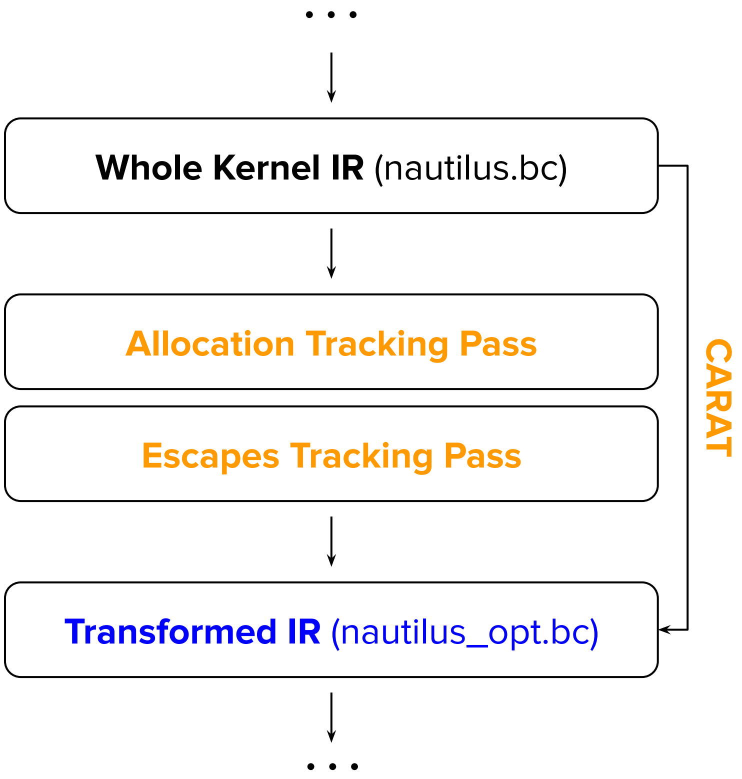
Protections

- Protections are also implemented as a middle-end LLVM transform --- **injecting IR** directly into *nautilus.bc*

Allocation Tracking

Escapes Tracking

Protections



Allocation Tracking

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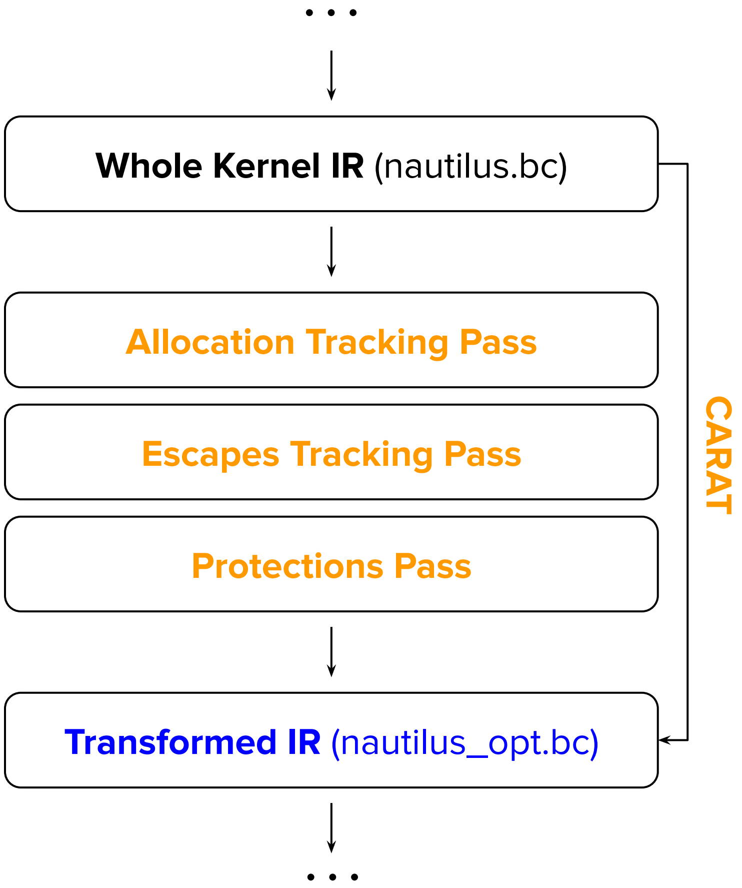
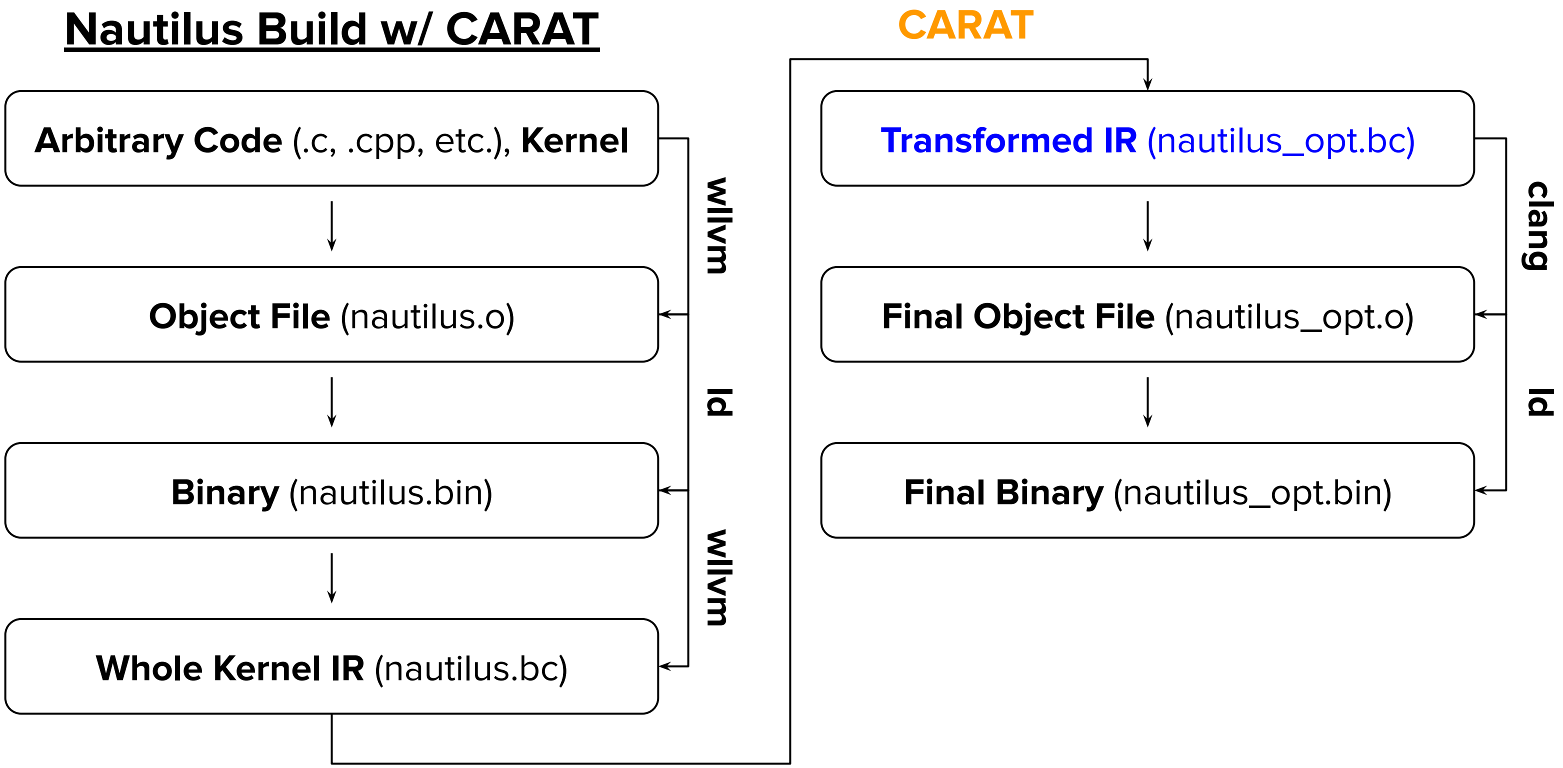
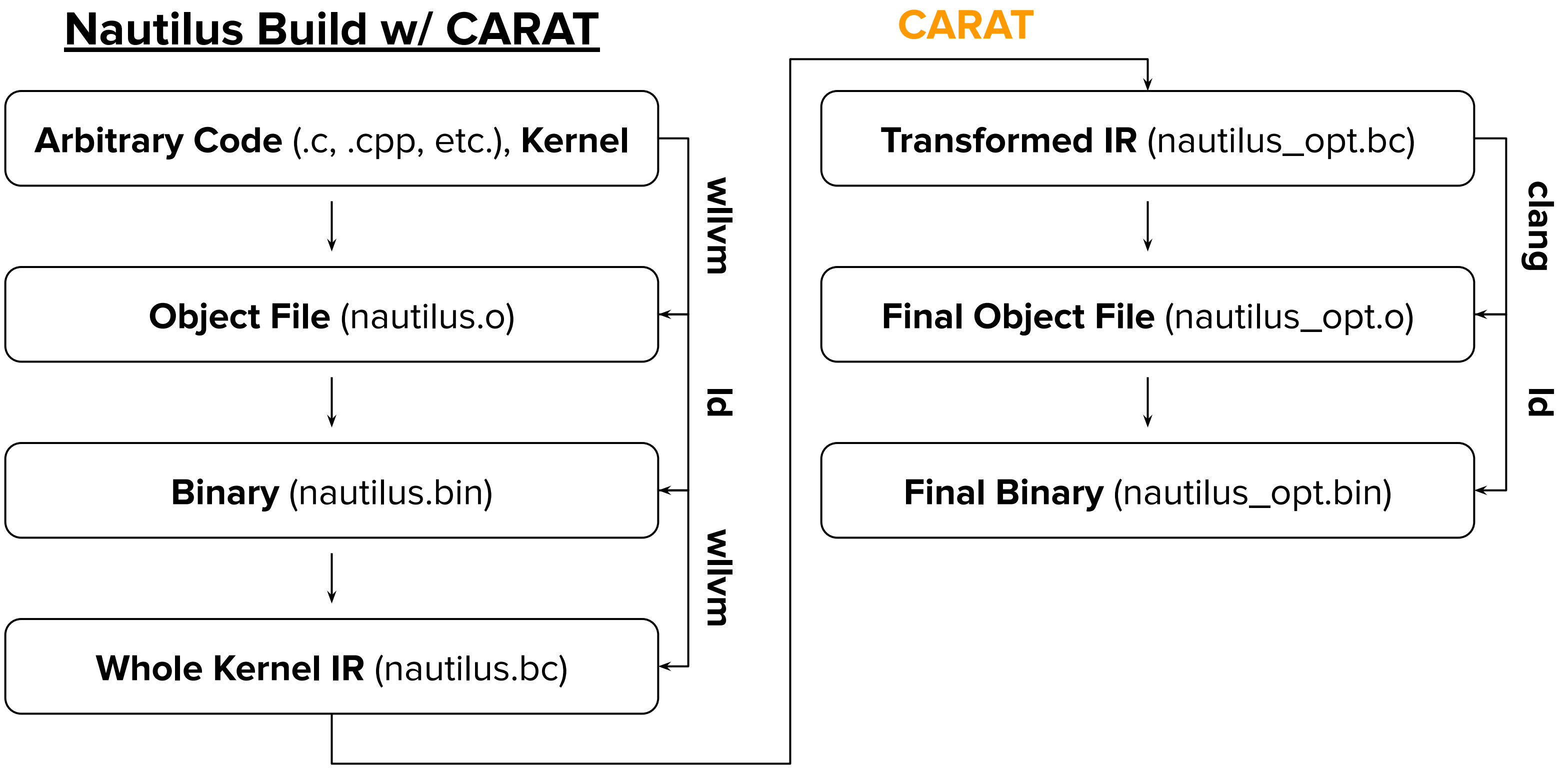


KARAT: Compiler Mechanics



KARAT: Compiler Mechanics



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- **Kernel CARAT --- “KARAT”**
  - CARAT in Nautilus
  - Compiler Mechanics
  - **Runtime Mechanics**
- Next Steps

KARAT: Runtime Mechanics

- Original CARAT runtime has the following features:
  - **Track** memory allocations and escapes
  - Perform **address translation** dynamically
  - Written in **C++**
  - Run at the **user level** and for **user** programs
- KARAT will be using a simplified and more accurate runtime:
  - Performs tracking via kernel **allocation** and **escapes table**
  - Essentially **no** address translation b/c of Nautilus' simple paging
  - Run at the **kernel level** and for **kernel** programs

KARAT: Runtime Mechanics

- What is the runtime?
  - **Compiler transforms** inject calls to the runtime
  - The **runtime** is built into the **kernel** itself
- **What does this look like?**
  - In reality, these will be injections in the LLVM-IR (**middle-end**)
  - We'll show an example of what the transformations and runtime invocations look like at the **source-code** level --- for simplicity

KARAT: Runtime Mechanics

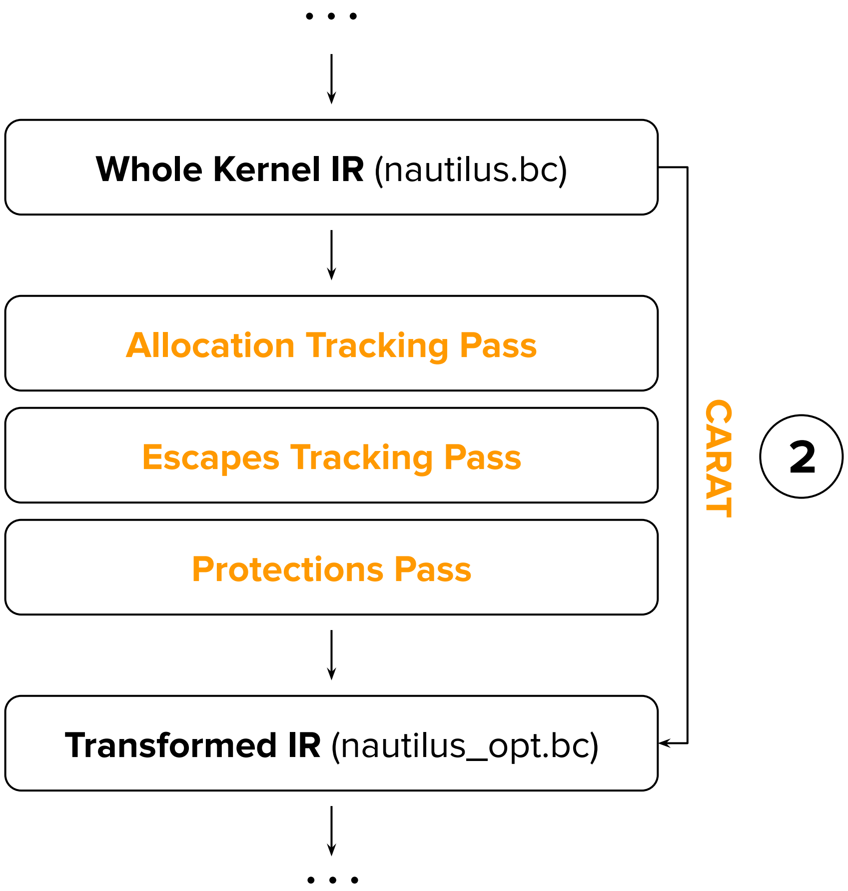
- Example **user code** before any compiler transformation

```c
int main() {
    // Array of 100 ints
    int* x = (int*) malloc(sizeof(int)*100);

    x[2] = 2;

    int* y = &x[2];

    x[3] = 4;
    return 0;
}
```


. . .
Whole Kernel IR (nautilus.bc)
Allocation Tracking Pass
Escapes Tracking Pass
Protections Pass
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. . .
CARAT
2

KARAT: Runtime Mechanics

- Example **user code** before any compiler transformation

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    int* y = &x[2];

    x[3] = 4;
    return 0;
}
```

KARAT: Runtime Mechanics

- Example **user code** with **allocation/escapes** tracking transforms

```c
int main() {
    // Array of 100 ints
    int* x = (int*) malloc(sizeof(int)*100);
    AddToAllocationTable(x, sizeof(int)*100);
    x[2] = 2;

    int* y = &x[2];
    AddToEscapeTable(y);
    x[3] = 4;
    return 0;
}
```

Track **allocation** stored in **x**

Track the **escape** that points to the allocation

KARAT: Runtime Mechanics

- Example **user code** with **protections** transforms

```
int main() {
    // Array of 100 ints
    int* x = (int*) malloc(sizeof(int)*100);
    AddToAllocationTable(x, sizeof(int)*100);
    if(&x[0] < LowerBound || &x[99] > UpperBound){
        abort();
    }
    x[2] = 2;
    // Variable y is stored on our stack and we know it doesn't go over
    int* y = &x[2];
    AddToEscapeTable(y);
    //We know that the entire x array is fine from the first check we performed
    x[3] = 4;
    return 0;
}
```

Check if accessed memory location is a part of the **aspace**

KARAT: Runtime Mechanics --- Put Altogether

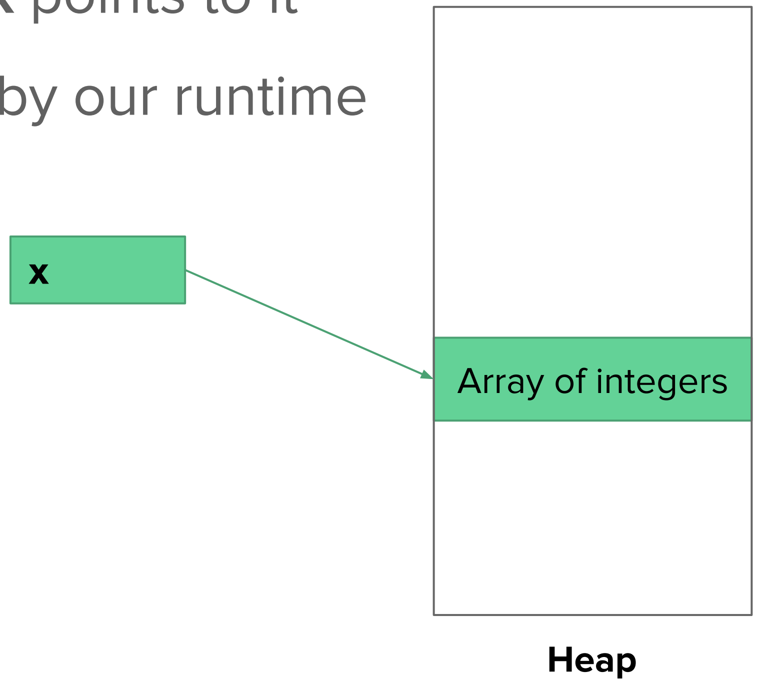
- Why do we track **allocations** and **escapes**?
  - To have a precise picture of memory at every execution step
  - To allocate and deallocate memory without corrupting the already allocated stuff
- This is where **patching** comes in
  - When the kernel needs to move physical memory
  - We can no longer rely on page tables to ensure pointers are correct
  - Pointers need to be updated by the kernel using information we tracked

KARAT: Runtime Mechanics --- Allocations

- An array is initialized, variable **x** points to it
- **x** is an **allocation** --- is tracked by our runtime

x	Length = 100 Escapes = { }
...	...

Allocation Map

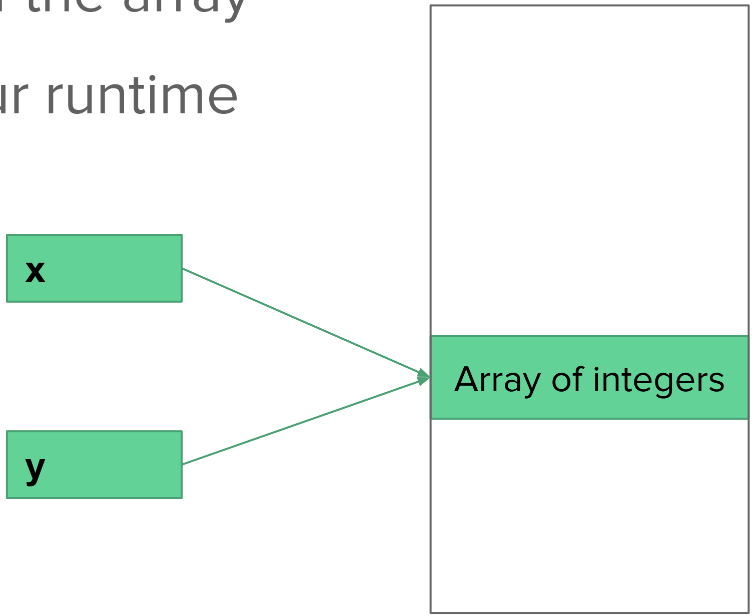


KARAT: Runtime Mechanics --- Escapes

- Variable **y** is a pointer to part of the array
- **y** is an **escape** --- tracked by our runtime

x	Length = 100 Escapes = { **y** }
…	…

Allocation Map



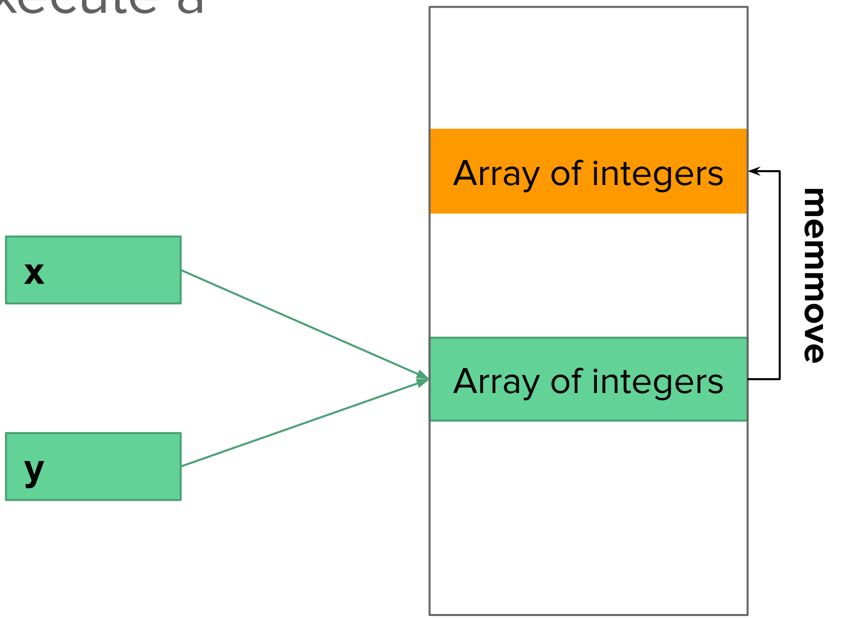
Heap

KARAT: Runtime Mechanics --- Moves and Patches

- Let's say the kernel needs to execute a **move** for the array of integers

x	Length = 100 Escapes = { **y** }
...	...

Allocation Map



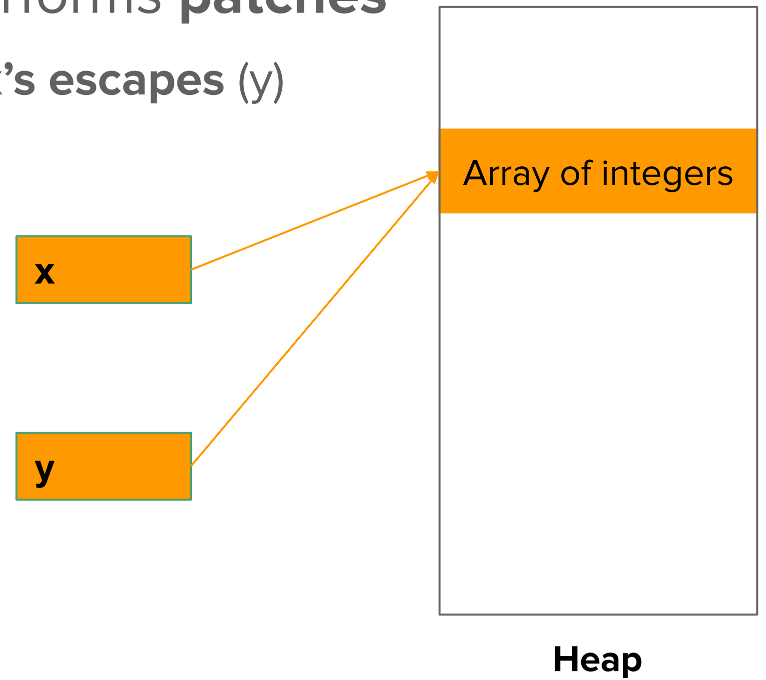
Heap

KARAT: Runtime Mechanics --- Moves and Patches

- After the move, the runtime performs **patches**
  - What **x** is pointing to AND what **x's escapes** (y) point to

x	Length = 100 Escapes = { **y** }
...	...

Allocation Map



KARAT: Runtime Mechanics

- Porting from C++ to C is complicated
- A lot of data structures that exist in the C++ STL **don’t exist** in C or in Nautilus
  - We built them ourselves --- **sets** and **maps** --- using **skiplists**
- We also have to confirm that the runtime **does not conflict** with Nautilus’ buddy allocator system

Similar methods exist for **`realloc`**, **`calloc`**, etc.

`AddToAllocationTable`

`RemoveFromAllocationTable`

`AddToEscapeTable`

Runtime Invocations

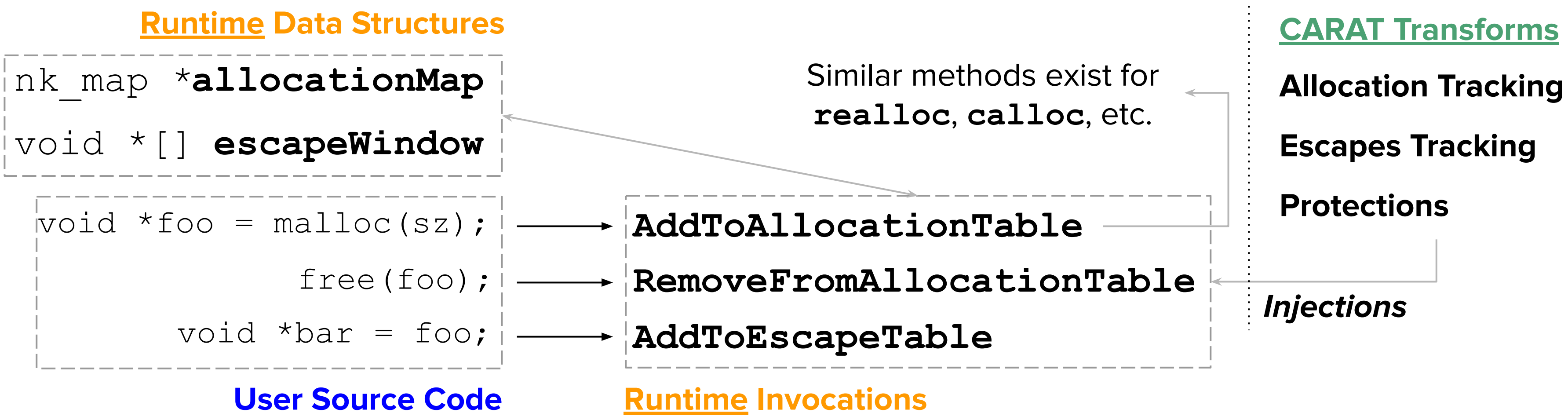
CARAT Transforms

Allocation Tracking

Escapes Tracking

Protections

Injections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CARAT Transforms
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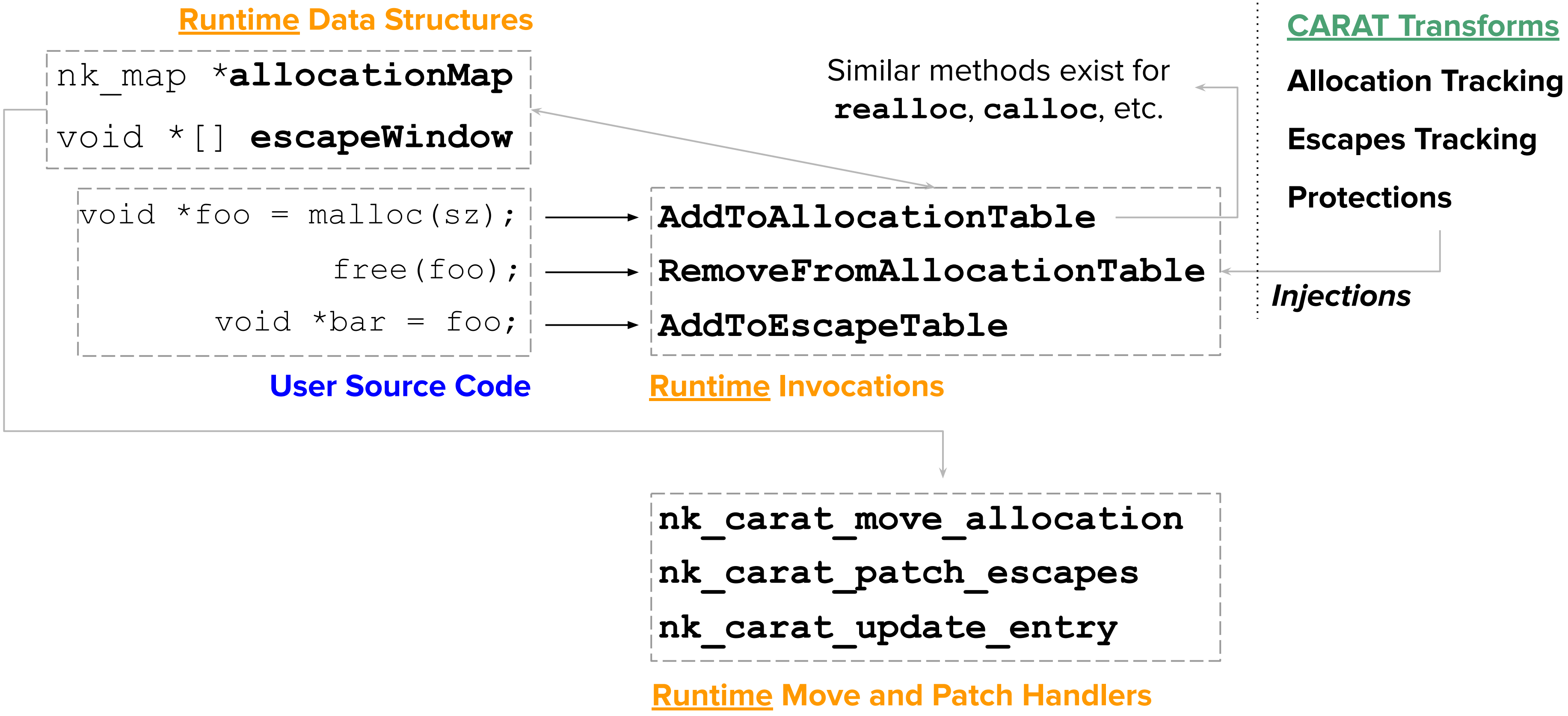
free(foo);
void *bar = foo;
AddToAllocationTable
RemoveFromAllocationTable
AddToEscapeTable
Injections
User Source Code
Runtime Invocations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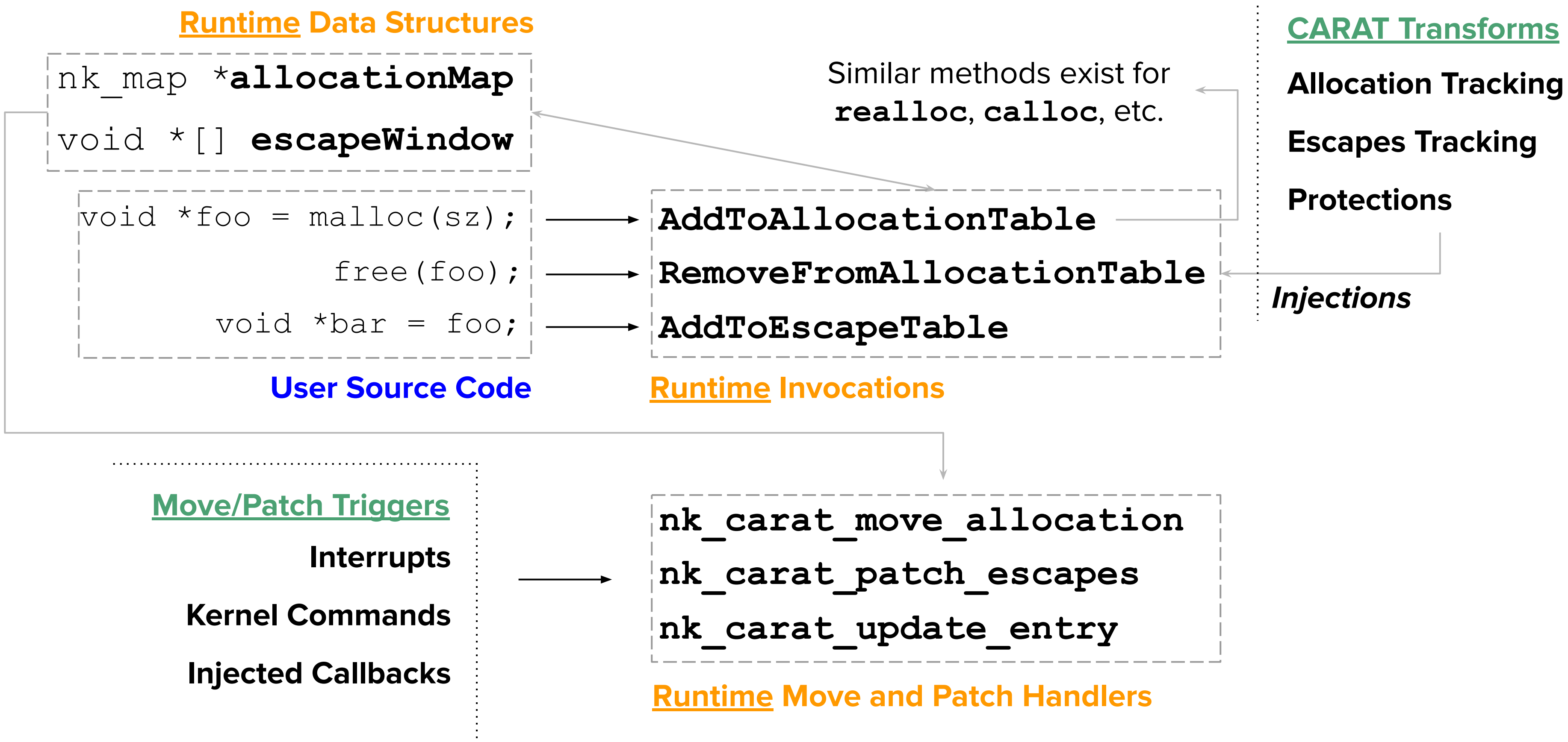
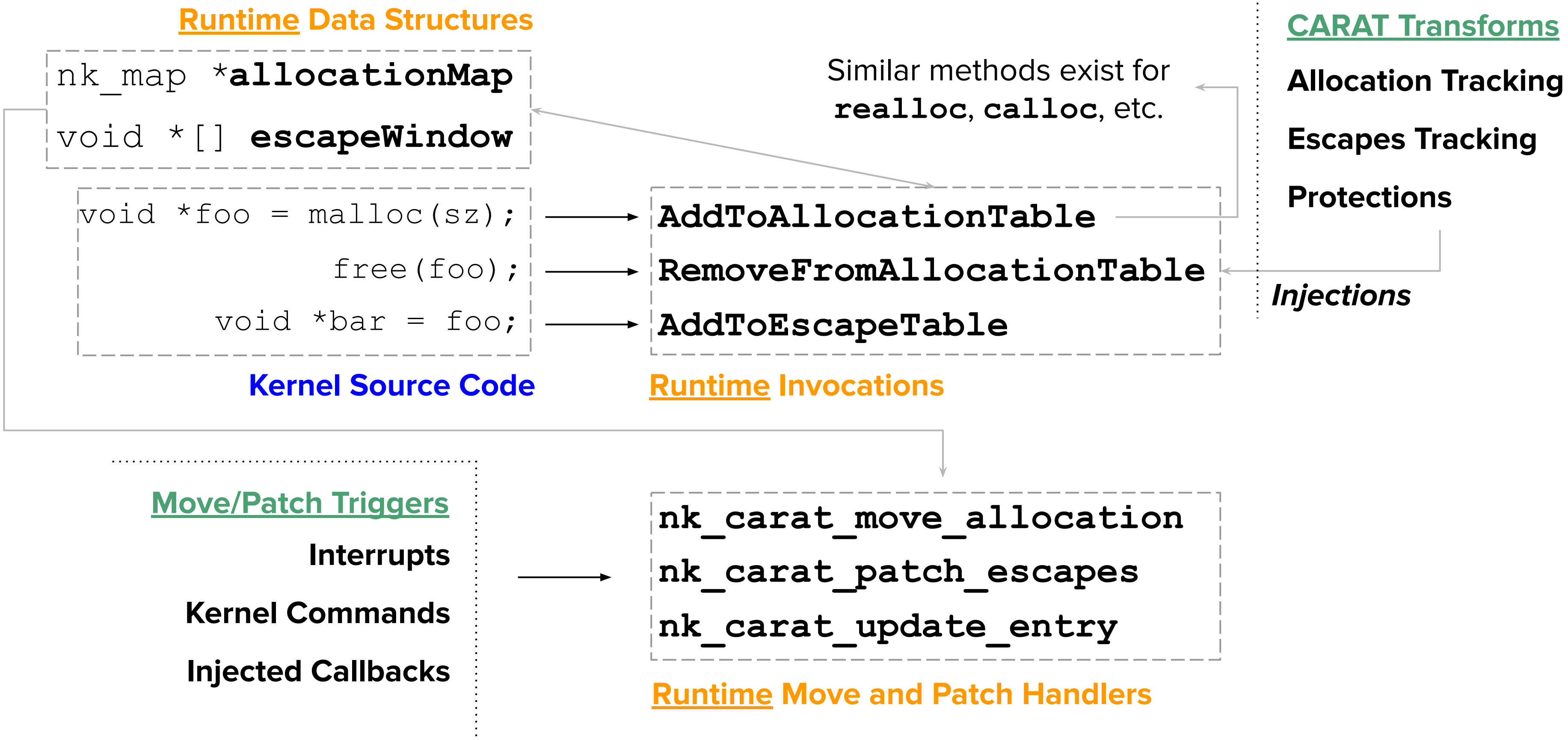
nk_carat_move_allocation
nk_carat_patch_escapes
nk_carat_update_entry
Runtime Move and Patch Handlers


Runtime Data Structures
nk_map *allocationMap
void *[] escapeWindow
void *foo = malloc(sz);
free(foo);
void *bar = foo;
User Source Code
AddToAllocationTable
RemoveFromAllocationTable
AddToEscapeTable
Runtime Invocations
Similar methods exist for
realloc, calloc, etc.
CARAT Transforms
Allocation Tracking
Escapes Tracking
Protections
Injections
Move/Patch Triggers
Interrupts
Kernel Commands
Injected Callbacks
nk_carat_move_allocation
nk_carat_patch_escapes
nk_carat_update_entry
Runtime Move and Patch Handlers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Runtime Move and Patch Handlers

Outline

- CARAT --- Overview
- Kernel CARAT --- “KARAT”
    - CARAT in Nautilus
    - Compiler Mechanics
    - Runtime Mechanics
- **Next Steps**

Next Steps

- Compilation
  - Finish up the **protections pass**
- Runtime
  - Build a more realistic policy for Nautilus to move memory and test with KARAT --- involving **interrupts** or **injected callbacks**
- Write benchmarks in Nautilus to test a working version of KARAT
- Run Nautilus with KARAT on bare metal (KNL Phi, R415, etc.)