# CSci 5271
## Guest Lecture

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# Software-based Fault Isolation

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## Need for extensibility

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- Applications can incorporate independently developed modules
  - Operating System
    - Add new file system
  - Database Management System
    - User-defined data type
  - Browser
    - Multimedia editor



## Problem with extensions

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- Security and Reliability
- Extensions may be
  - Malicious
  - Vulnerable
  - Faulty
- Solution:
  - Isolate from others



## Isolation option 1

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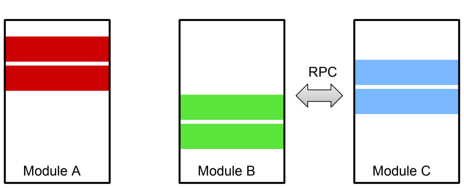
- Hardware-based isolation
  - Place each module in its own address space
  - Communicate via RPC






## Isolation option 1

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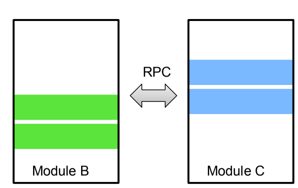
- Hardware-based isolation
  - Place each module in its own address space
  - Communicate via RPC
    - Switch to kernel mode
    - Copy arguments
    - Save/Restore registers
    - Switch address spaces
    - Return to user mode



## Isolation option 2

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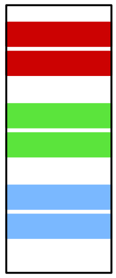
- Software-based isolation
  - All modules in same virtual address
  - Protect them from each other
  - Provide efficient communication





## Isolation option 2

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- Software-based isolation
  - All modules in same virtual address
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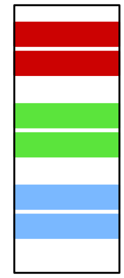



# Efficient Software-based Fault Isolation

Robert Wahbe, Steven Lucco, Thomas E. Anderson, Susan L. Graham
SOSP 1993

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## Goal

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- Protect the rest of an application from a buggy/malicious module on **RISC** architecture
- Separate untrusted code
  - Define a fault domain
  - Prevent the module from jumping or writing outside of it
  - While letting efficient communications



## Fault Domain

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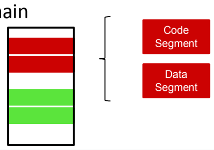
- Load untrusted extension into its own fault domain
  - Code Segment
  - Data Segment
- Security Policy:
  - No code is executed outside of fault domain
  - No data changed outside of fault domain
    - Some protect load, too






## Unsafe Instructions

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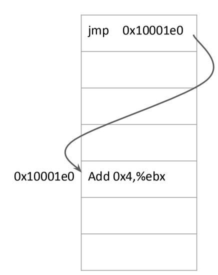
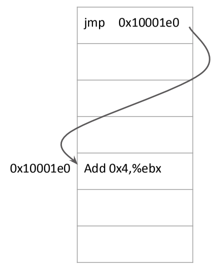
- Jump or store instructions
  - Change Control flow
  - Change data
- Addressing issue
  - jmp 0x10001e0



## Unsafe Instructions

University of Minnesota

- Jump or store instructions
  - Change Control flow
  - Change data
- Addressing issue
  - jmp 0x10001e0
  - mov %eax,0x11020028

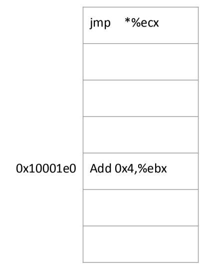





## Unsafe Instructions

University of Minnesota

- Jump or store instructions
  - Change Control flow
  - Change data
- Addressing issue
  - jmp 0x10001e0
  - jmp *%ecx
  - mov %eax,0x11020028
  - mov $0x1b80,(%ecx)






## Segment ID

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- Within a segment
  - Addresses share unique pattern of upper bits


## Segment Matching

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- Insert checking code before unsafe instruction
  - check segment ID of target address
- Use dedicated registers

dedicated-reg ⇐ target-address
scratch-reg ⇐ (dedicated-reg >> shift-reg)
if scratch-reg == segment-reg:
    jmp/mov using dedicated-reg

## Segment Matching

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- Needs 4 dedicated registers
- Checking code must be atomic
- Exact location of fault can be detected
- Runtime overhead
  - 4 extra instructions

## Address Sandboxing

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- Ensure, do not check!
- Before each unsafe instruction
  - Set upper bit of target address to correct segment ID

dedicated-reg ⇐ target-address & and-mask
dedicated-reg ⇐ dedicated-reg | segment-reg
jmp/mov using dedicated-reg

## Address Sandboxing

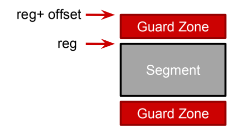


- Prevents faults
- Needs 5 dedicated registers
- 2 extra instructions
  - less overhead compared to segment matching

## Optimizations



- register-plus-offset mode
  - store value, offset(reg)
  - offset is in the range of -64K to +64K
  - mov %esi,0x8(%edx)




## Optimizations

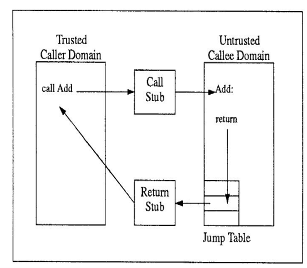


- Stack pointer
  - Just sandbox it when it is set (beginning of a function)
  - Ignore sandboxing for small changes (push, pop)
  - Works because of guard zones

## Cross Fault Domain Communication



- Host to an untrusted module
- Untrusted module to host
- Call/Return Stub
  - For each pair of fault domains






## Cross Fault Domain Call



- Trusted call/return stub
  - copy parameters
  - switch execution stack
  - maintain values of CPU registers
  - no traps or address space switching
    - faster
  - returns via jump table
    - jump targets are immediates
    - a legal address in target fault domain

## Implementation



- Change the compiler
  - emit encapsulation code into distrusted code
- At the load time
  - check the integrity of encapsulation code
  - Verifier

## Verifier



- Responsible for checking encapsulation instructions just before execution start
- Challenge:
  - indirect jump
- Hint:
  - every store/jump uses dedicated registers
- Look for changes in dedicated registers
  - any change means beginning of a check region
  - verify the integrity of check region





What about CISC architectures?!
x86



# Evaluating SFI for a CISC Architecture
(PittSFIeld)

Stephen McCamant, Greg Morrisett
USENIX 2005

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## CISC Architectures



- RISC Architecture
  - Fixed length instructions
  - More CPU registers
- Intel IA-32 (aka x86-32)
  - Variable length instructions
  - Less CPU registers
- Classical SFI is not applicable here



## CISC Architectures



- Processor can jump to any byte
- Hard to make hidden instructions safe
- Solution: Instruction Alignment

```
         push %esi
     mov $0x56,%dh | sbb $0xff,%al | inc %eax | or %al,%dh
movzbl 0x1c(%esi),%edx |    incl 0x8(%eax)        ...
0f b6      56        1c       ff       40      08     c6
```



## Alignment



- Divide memory into 16-byte chunks
- No instruction is allowed to cross chunk boundary
- Target of jumps placed at the beginning of chunks
- Call instructions placed at the end of chunk

## Alignment

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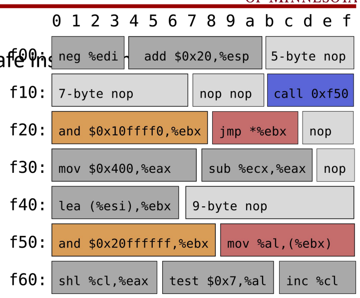
- Use *NOP* for padding
- No separation of an unsafe ins






## Jumps

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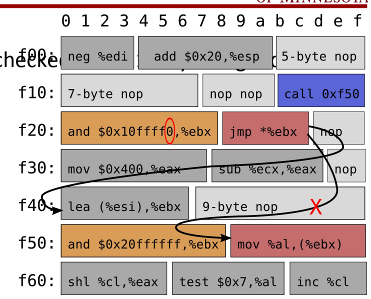
- Chunks are atomic
- Jump destinations are checke






## Optimization: AND-only Sandboxing

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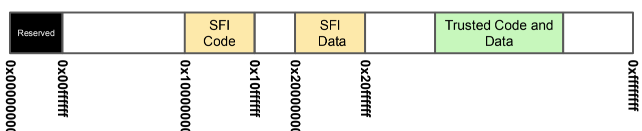
- Choose code and data region addresses carefully
- Their ID just has one bit set
- Reduces sandboxing sequence to just one instruction






## Example

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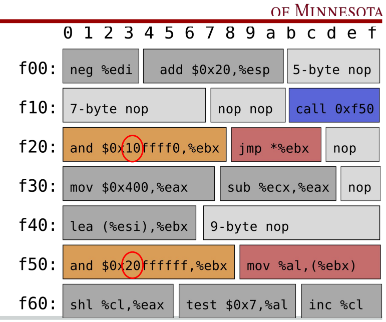




## Verification

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- Statically check
  - No jump to outside of code region
  - No store to outside of data region
- Before each unsafe jump or store there should be a sandboxing AND
- The sandboxing AND should not be the last instruction in a chunk



## Performance overhead

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- Implemented prototype
  - named PittSFIeld
- Average module overhead: 21%
- But the overall execution can be improved because of faster communications
  - no trap, RPC, etc

## Native-client: A Sandbox for Portable, Untrusted x86 Native Code

Bennet Yee, et al.
IEEE S&P, 2009

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## Google Native Client

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- Browser Plugin (Google Chrome)
  - Allows execution of untrusted C/C++ code in browser
- Browser?! Native Code?!
  - Yes! browsers are new platform for applications
- Gives Browser plugins performance of native code
- Ships by default since Chrome 14



## Sandboxing

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- Inner Sandbox
  - Code sandboxing
    - Alignment and address sandboxing
    - Check branch target addresses
  - Data Sandboxing
    - segmented addressing mode supported by x86_32
- Outer Sandbox
  - Controls system calls issued by native code
  - Whitelist



## NaCl Architecture

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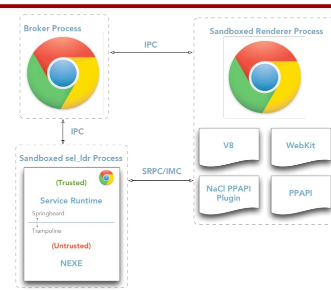


Source: https://media.blackhat.com/bh-us-12/Briefings/Rohlf/BH_US_12_Rohlf_Google_Native_Client_Slides.pdf



## Inner Sandbox

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- On x86_32
  - Sandboxing via segmented memory
  - Used to separate trusted from untrusted code/data
  - Modified when switching between trusted/untrusted
  - `%cs` code
  - `%ds` data
  - `%gs` thread local storage
  - `%ss %es %fs` all set to `%ds`
- On x86_64
  - mov/branch alignment, guard pages
  - `r15` keeps base address of an aligned 4GB range



## Native Client Toolchain

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- Modified GCC and GAS
  - To emit sandboxing instructions
- Final executable has ELF file structure (called NEXE)
  - Can be disassembled using standard tools
  - objdump -d

```
naclcall   %ebx   ---->   and  $0xffffffe0,%ebx
                          call      *%ebx

nacljmp  %ecx     ---->   and  $0xffffffe0,%ecx
                          jmp  *%ecx
```

# Alignment

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- Divide memory into 32-byte Bundles
- Target of jumps placed at the beginning of bundles
- No instruction is allowed to cross bundle boundary

```
                              ...
1060451:    83 c8 01                 or     $0x1,%eax
1060454:    88 41 28                 mov    %al,0x28(%ecx)
1060457:    8b 0e                    mov    (%esi),%ecx
1060459:    8b 51 04                 mov    0x4(%ecx),%edx
106045c:    85 d2                    test   %edx,%edx
106045e:    66 90                    xchg   %ax,%ax

1060460:    0f 88 9a 01 00 00        js     1060600
1060466:    8b 01                    mov    (%ecx),%eax
1060468:    8d 3c 95 00 00 00 00     lea    0x0(,%edx,4),%edi
106046f:    89 d6                    mov    %edx,%esi
1060471:    83 ea 01                 sub    $0x1,%edx
1060474:    83 e6 07                 and    $0x7,%esi
1060477:    83 fa ff                 cmp    $0xffffffff,%edx
106047a:    8d b6 00 00 00 00        lea    0x0(%esi),%esi

1060480:    c7 04 38 84 06 03 11     movl   $0x11030684,(%eax,%edi,1)
1060487:    8d 47 fc                 lea    -0x4(%edi),%eax
106048a:    0f 84 70 01 00 00        je     1060600
                              ...
```



# Alignment

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- Divide memory into 32-byte Bundles
- Call instructions placed at the end of bundles
  - For the sake of return address alignment

```
10ee700:    55                       push   %ebp
10ee701:    89 e5                    mov    %esp,%ebp
10ee703:    83 ec 18                 sub    $0x18,%esp
10ee706:    c7 04 24 2c 5e 01 11     movl   $0x11015e2c,(%esp)
10ee70d:    8d b4 26 00 00 00 00     lea    0x0(%esi,%eiz,1),%esi
10ee714:    8d bc 27 00 00 00 00     lea    0x0(%edi,%eiz,1),%edi
10ee71b:    e8 a0 72 f5 ff           call   10459c0

10ee720:    89 ec                    mov    %ebp,%esp
10ee722:    5d                       pop    %ebp
10ee723:    59                       pop    %ecx
10ee724:    83 e1 e0                 and    $0xffffffe0,%ecx
10ee727:    ff e1                    jmp    *%ecx
                              ...
```



# Service Runtime

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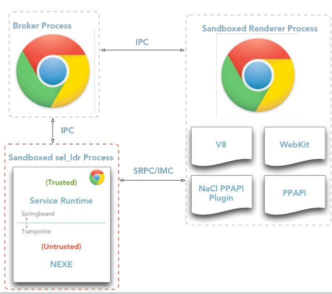


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# Service Runtime

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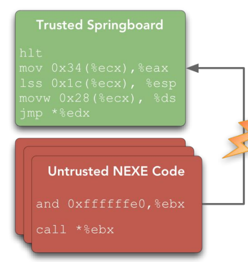


The untrusted NEXE code is unable to transfer control to an arbitrary location in the trusted Springboard due to the alignment mask before the call. It may only execute the first instruction, which is a *hlt*

Source: https://media.blackhat.com/bh-us-12/Briefings/Rohlf/BH_US_12_Rohlf_Google_Native_Client_Slides.pdf



# Service Runtime

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- No existing or new memory allocations may be marked as executable at runtime
  - This guarantees only validated code pages have executable permissions
- NaCl syscall
  - ~ 30 syscalls allowed
  - Basic operations such as open, close, read, write, ioctl, mmap, munmap, stat, _exit and a few others



# Validator

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- Disassembles all NEXE instructions
- Starts at trusted 32 byte aligned entry point
- Exits on any blacklisted instructions
  - Privileged instructions
  - Instructions that modify segment registers
  - ret
  - sysenter

# CBI NaCl

or
Cross-Bundle Instruction Native Client

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## Padding vs Performance

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- Change NaCl padding scheme
  - Pad removal
  - Greedy Algorithm
- Multipass Validator
  - We must guarantee sandboxing policy enforcement
  - Appropriate changes in validator



## Types of Padding

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- Indirect jump target
  - Will be placed at the next bundle start
- Call instruction
  - Will be placed at the end of the bundle
- Cross bundle instruction
  - Will be pushed to the start of next bundle



## Types of Padding

University of Minnesota

- Indirect jump target
  - Will be placed at the next bundle start
- Call instruction
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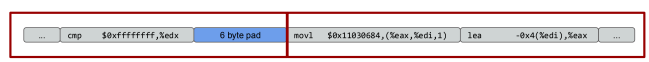
- Cross bundle instruction
  - Will be pushed to the start of next bundle
  - Conservative






## Pad Removal

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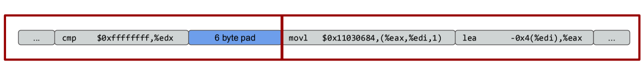




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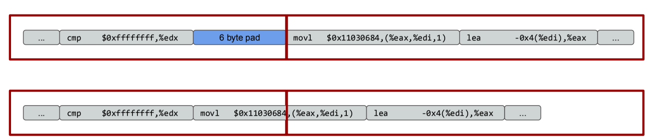

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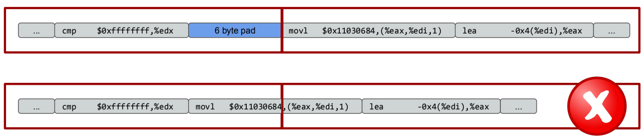




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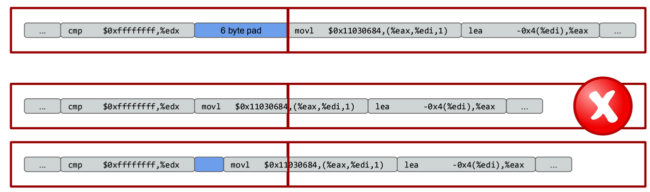




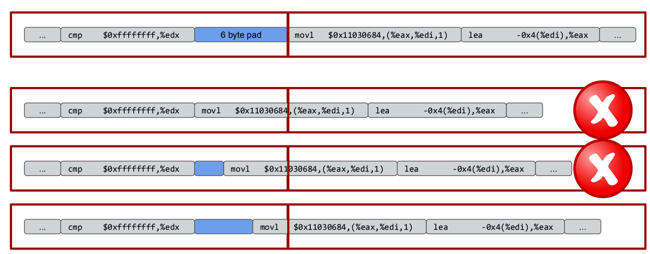

## Pad Removal






## Pad Removal

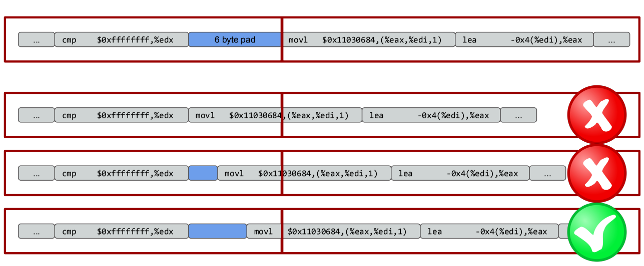







## Pad Removal








## NaCl Validator



- One pass: from the start to the end of code
- Maintains two bitmaps: *valid* and *target*
- At each address checks the instruction
- If a valid instruction marks it in *valid* and advance by instruction size
- If indirect branch checks masking instruction presence
- If direct branch, the destination is marked in *target*
- At the end *target* and *valid* are compared together

## Multipass Validator

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- Challenge: Cross-Bundle Instructions

```
                                   ...
1060451:     83 c8 01                 or     $0x1,%eax
1060454:     88 41 28                 mov    %al,0x28(%ecx)
1060457:     8b 0e                    mov    (%esi),%ecx
1060459:     8b 51 04                 mov    0x4(%ecx),%edx
106045c:     85 d2                    test   %edx,%edx
106045e:     66 90                    xchg   %ax,%ax

1060460:     0f 88 9a 01 00 00        js     1060600
1060466:     8b 01                    mov    (%ecx),%eax
1060468:     8d 3c 95 00 00 00 00     lea    0x0(,%edx,4),%edi
106046f:     89 d6                    mov    %edx,%esi
1060471:     83 ea 01                 sub    $0x1,%edx
1060474:     83 e6 07                 and    $0x7,%esi
1060477:     83 fa ff                 cmp    $0xffffffff,%edx
106047a:     8d b6 00 00 00 00        lea    0x0(%esi),%esi

1060480:     c7 04 38 84 06 03 11     movl
$0x11030684,(%eax,%edi,1)
1060487:     8d 47 fc                 lea    -0x4(%edi),%eax
106048a:     0f 84 70 01 00 00        je     1060600
                                   ...
```



## Multipass Validator

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- Challenge: Cross-Bundle Instructions
- Multipass: start validation from every crossing point
  - Bundle start
  - Stop if reached to an already validated instruction

```
                                   ...
1060451:     83 c8 01                 or     $0x1,%eax
1060454:     88 41 28                 mov    %al,0x28(%ecx)
1060457:     8b 0e                    mov    (%esi),%ecx
1060459:     8b 51 04                 mov    0x4(%ecx),%edx
106045c:     85 d2                    test   %edx,%edx
106045e:     66 90                    xchg   %ax,%ax

1060460:     0f 88 9a 01 00 00        js     1060600
1060466:     8b 01                    mov    (%ecx),%eax
1060468:     8d 3c 95 00 00 00 00     lea    0x0(,%edx,4),%edi
106046f:     89 d6                    mov    %edx,%esi
1060471:     83 ea 01                 sub    $0x1,%edx
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1060487:     8d 47 fc                 lea    -0x4(%edi),%eax
106048a:     0f 84 70 01 00 00        je     1060600
                                   ...
```



## Separate Compilation

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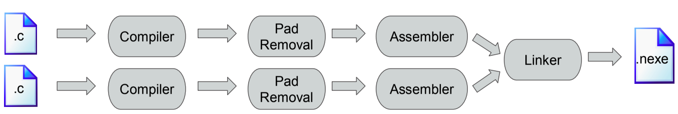
- We process each source file separately
  - Decide about the paddings to be removed
  - Assemble them into object files (using modified *GAS*)
  - Then link them together






## Relocations Problem

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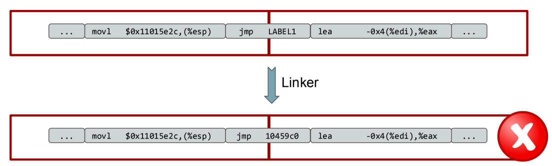




## Relocations Problem

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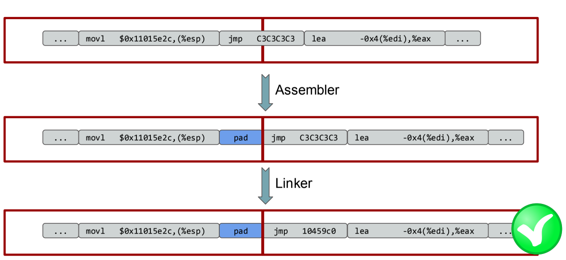




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Thank you

Any Question?