Code Injection Attacks on Harvard-Based Architecture Devices

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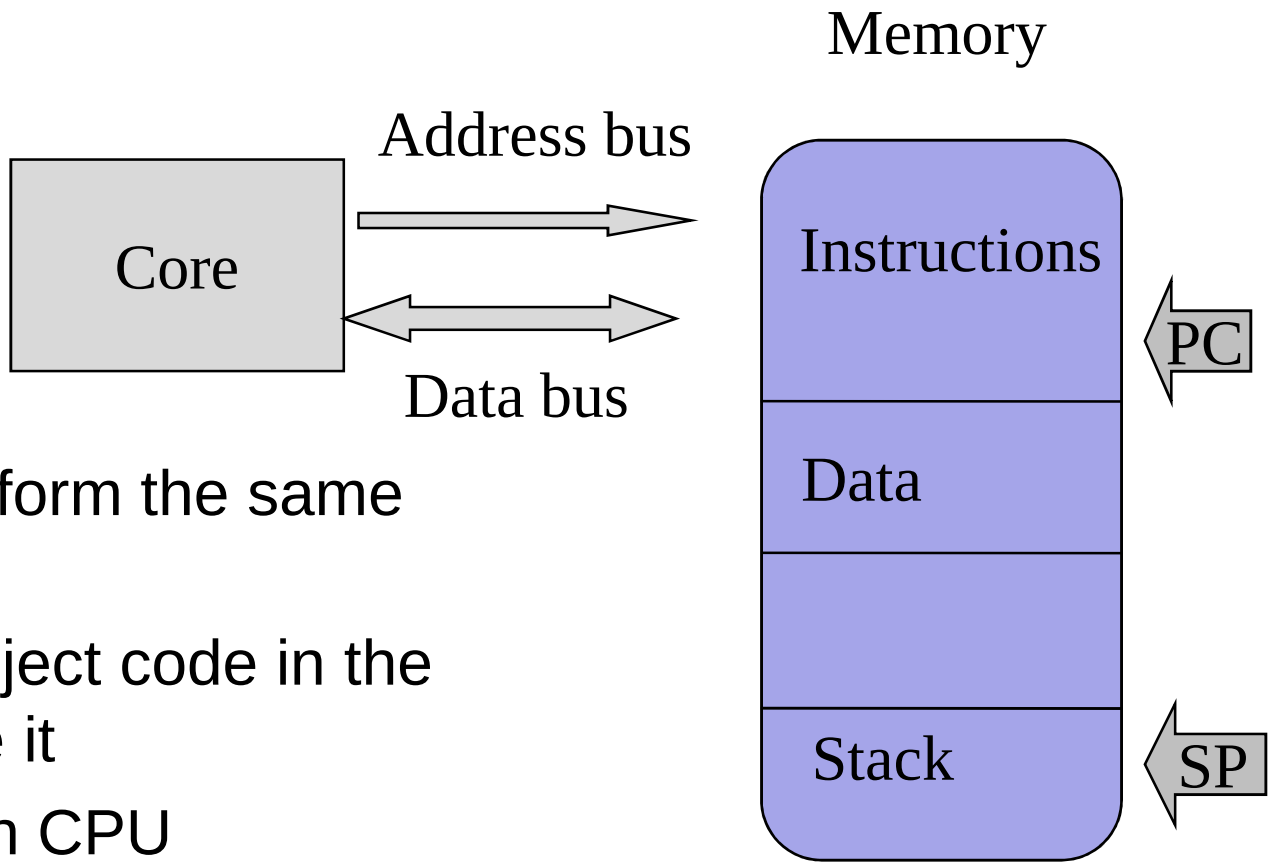
Outline

- Introduction
  - Standard code injection
  - Von Neumann and Harvard architectures
- Attack Description
  - Assumptions and Building Blocks
  - Building Blocks
    - Return Oriented Programming
    - Bootloader
    - Fake stack injection
  - Attack description
    - Attack Overview
    - Step by step attack description
- Conclusion
  - Results
  - Future work

Standard Code Injection Technique

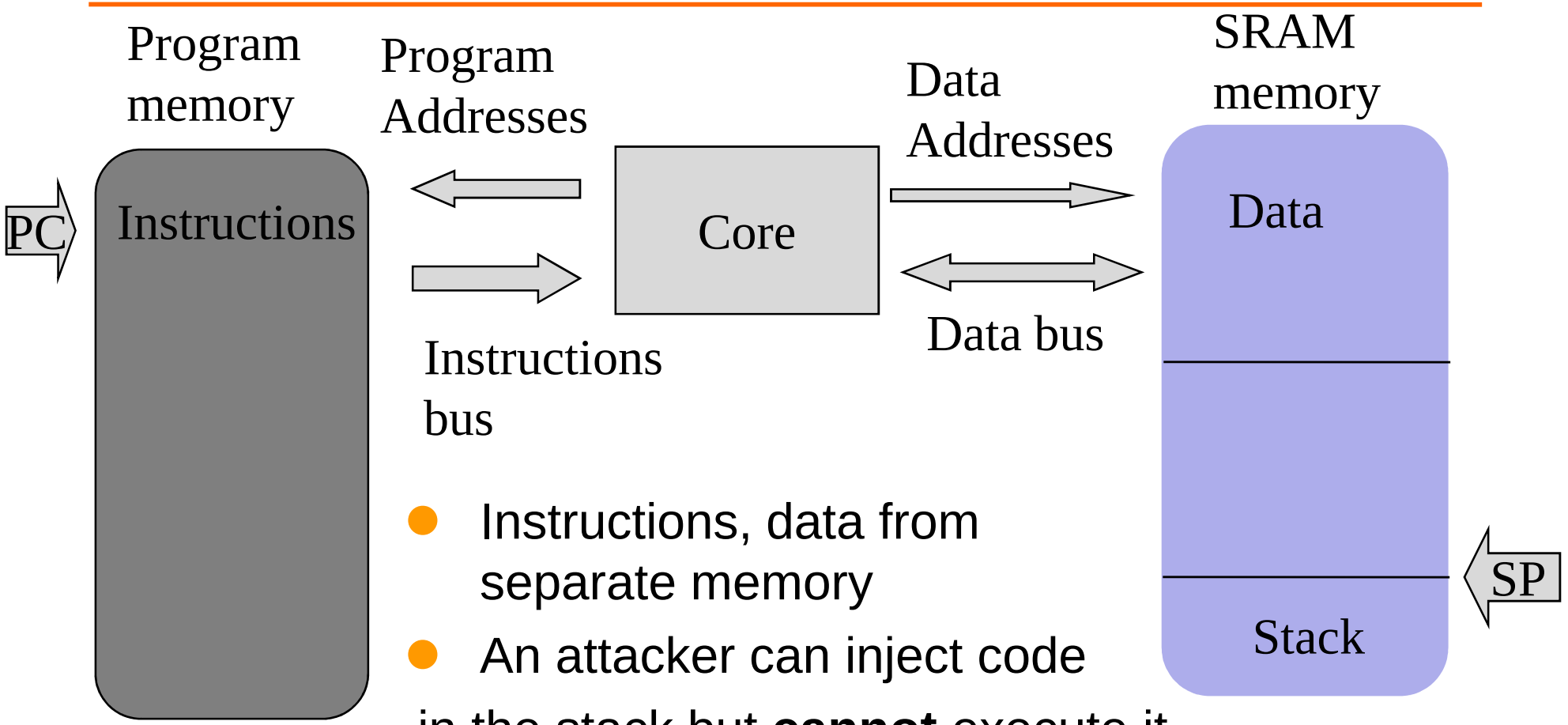
- Standard Code injection technique
  - Overflow a buffer allocated on stack
  - Overwrite return address
  - Inject instructions on the stack
  - Return to those instructions
- Possible on Von Neumann architecture
  - Can be prevented by making Stack Memory non executable (NX, PAX...)
  - Not possible on Harvard Architectures
- But Return Oriented Programming still enables to perform some « actions » (more details to come)
  - It's less powerful than code injection

Von Neumann Architecture



- Instructions, data form the same memory
- An attacker can inject code in the stack and execute it
- The most common CPU architecture

Harvard Architecture



- Instructions, data from separate memory
- An attacker can inject code

in the stack but **cannot** execute it

- Common in embedded systems (AVR, PIC) and DSP

Harvard Architecture

- It has been a common belief that code injection into a Harvard architecture is impossible!!…
- We show that this is not only possible but that code injection can also be performed on Harvard-Architecture constrained devices
- We were able to inject code into a Micaz WSN node
  - Constrained memory 4KB data 128KBytes program memory
  - Small network packets (28Bytes) on a IEEE 802.15.4 radio
  - Harvard Architecture (**ATMEL AVR** Atmega128)

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Attack Assumptions and Building Blocks

- Objective: perform remote code injection on a Micaz
- Assumptions :
  - A traditional stack based buffer overflow exists
  - Program Memory contents are known
  - A boot loader is present
- Building blocks :
  - Return Oriented Programming
    - To overcome the Harvard architecture
  - Bootloader
  - Fake stack injection
    - To overcome the packet and stack size limitation

Return Oriented Programming (ROP)

- Generalization of "*return to libc*" attacks
  - introduced by H. Shacham at CCS 2007 on the x86
- Useful when Code cannot be executed in the stack..
- But the control flow can be modified
  - Executes code already present in the program memory
  - By chaining sequences of instructions terminated by a return
    - Called Gadgets
  - Gadgets can be used to perform any action
    - When a Turing Complete Gadget set is available

ROP on Embedded Systems

- ROP is not practical on embedded systems
  - Packets and stack size limitations
  - Code size limitation (gadgets availability)
  - ⇨ Finding a *Turing Complete* Gadget set is unlikely
- But is an useful tool to perform code injection

Bootloader : a key element of the attack

- *Bootloader* is the program used for code update
- *Code update* is a must… otherwise
  - A device with a bug is “dead”
  - Think about pacemakers, sensors in cars ...
- The bootloader consists in :
  - Getting the image (from serial port , local storage , network …)
  - Copying the image to program memory
  - Uses dedicated instructions to copy a page from data to program memory
- We assume that if *remote* code update is present images are authenticated
  - *Otherwise attack is trivial*

Injecting code using ROP on sensors

- To inject code into a device, the attacker has to send a specially-crafted packet that contains:
  - Addresses of the gadgets
  - Gadgets' parameters
  - The malware code to be injected
  - Padding
- I.e. 305 bytes if malware is 256 bytes long

But this is not possible on Sensors…

- Packet and stack sizes are limited,
  - TinyOS packet payload maximum size is 28 bytes!
  - The number of gadgets that can be linked is limited

Fake stack injection

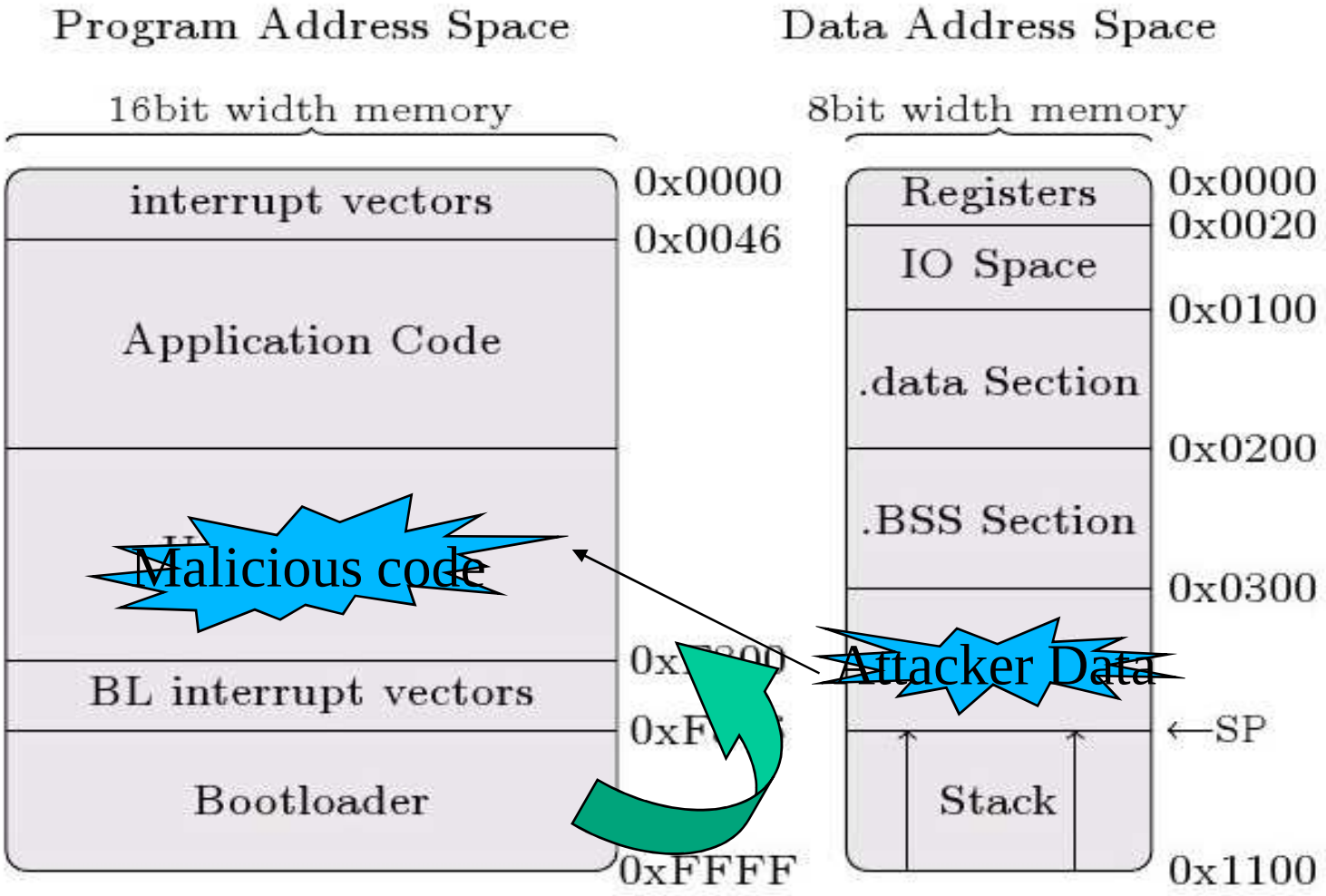
- Instead of sending one large packet with the large stack in it we send several small specially-crafted packets
  - To build a *fake stack*

- Each packet:
  - Contains one byte of the fake stack
  - Triggers a buffer overflow
  - Copies its fake stack byte into unused data memory, using ROP

- A final packet
  - Triggers a buffer overflow
  - Changes the Stack Pointer to the fake stack, using ROP
  - Executes several gadgets that copy the malware (contained into the fake stack) into the program memory

Attack detailed overview

- Injecting code in persistent flash memory



Illustration

- A specially-crafted packet (that contains the first byte of the fake stack) is sent

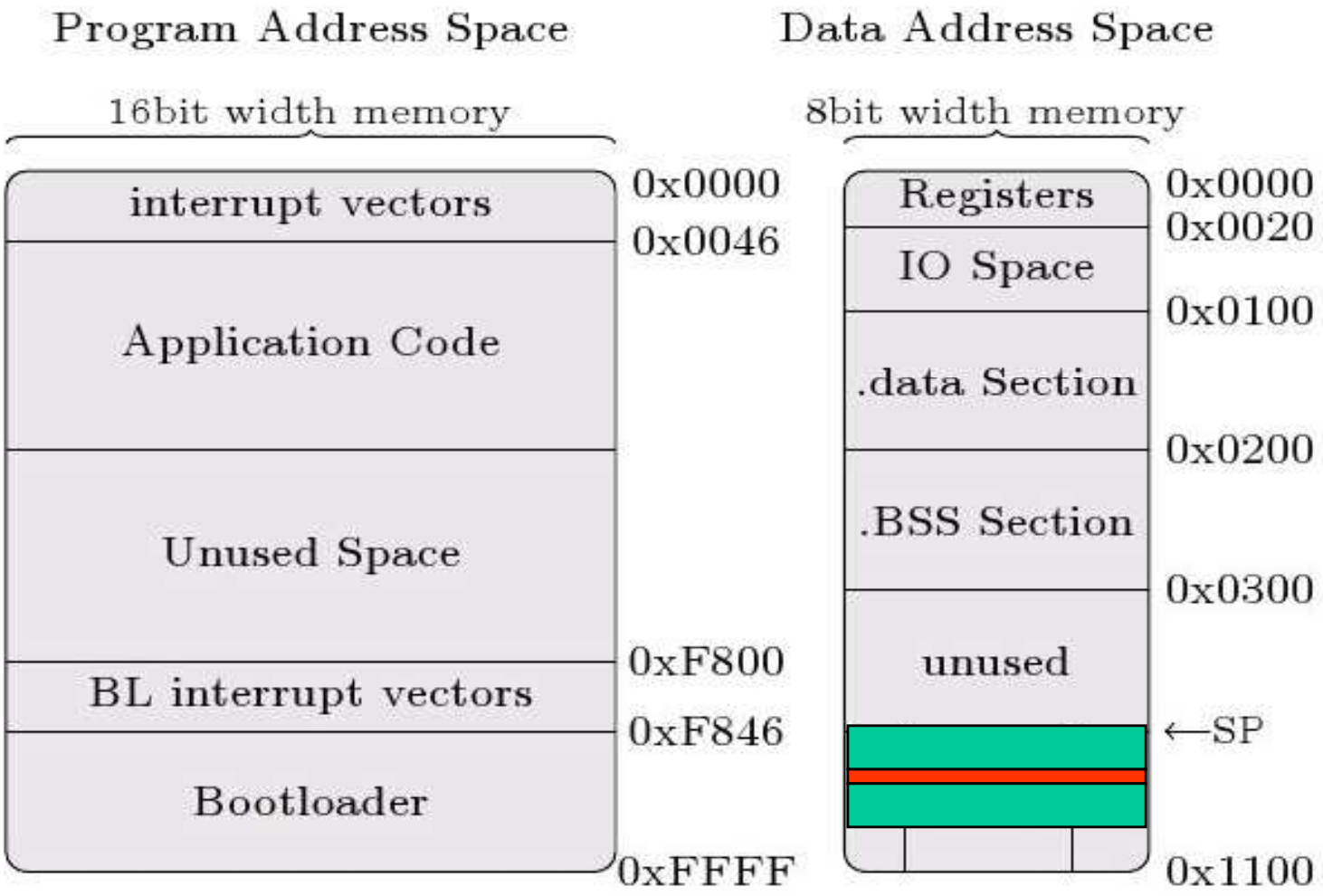
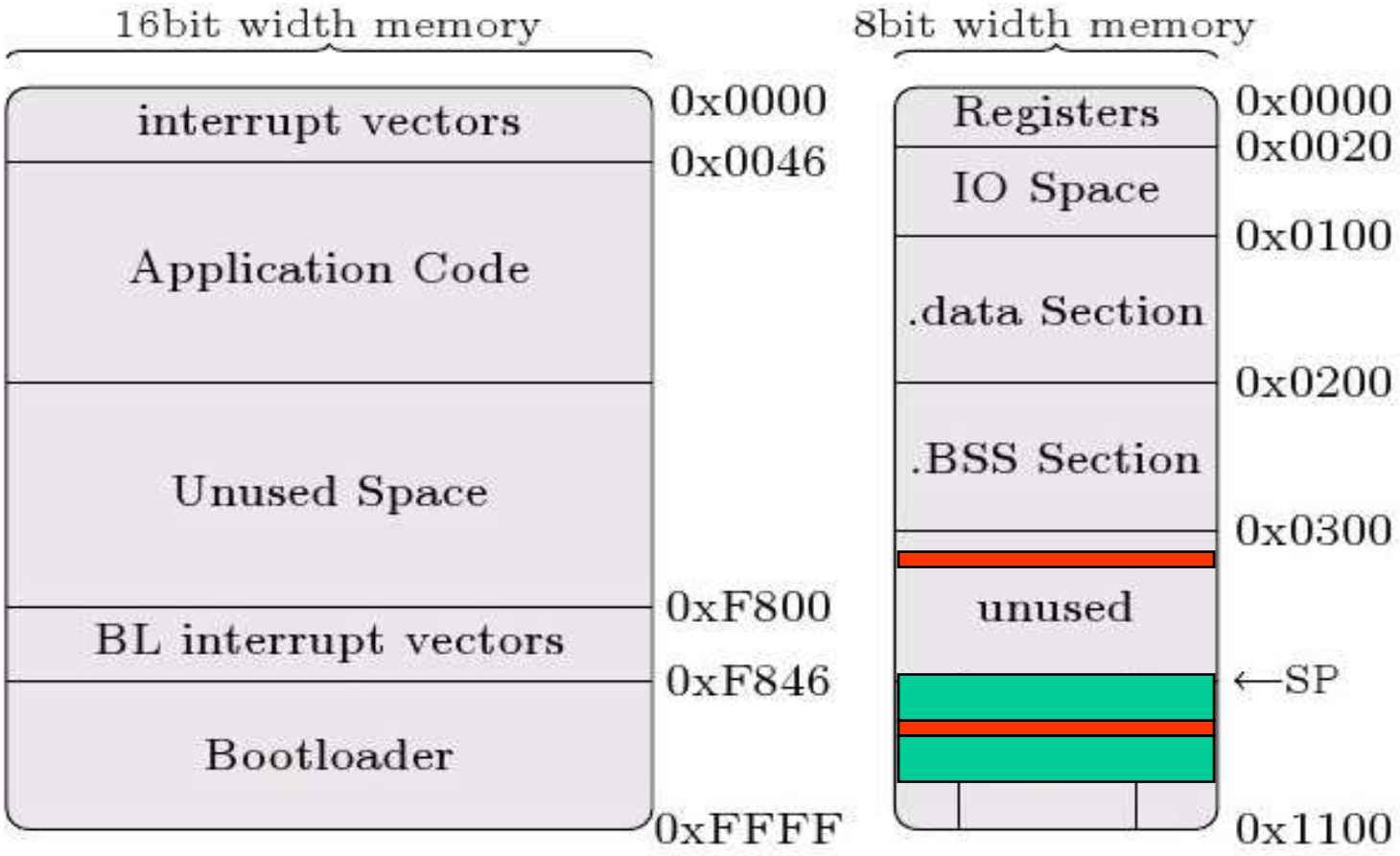


Illustration (2)

- This packet triggers a buffer overflow that copies its fake stack byte into the RAM memory
- And then reboots the node to restore consistent state



Writing a byte into memory (simplified)

- A gadget chain

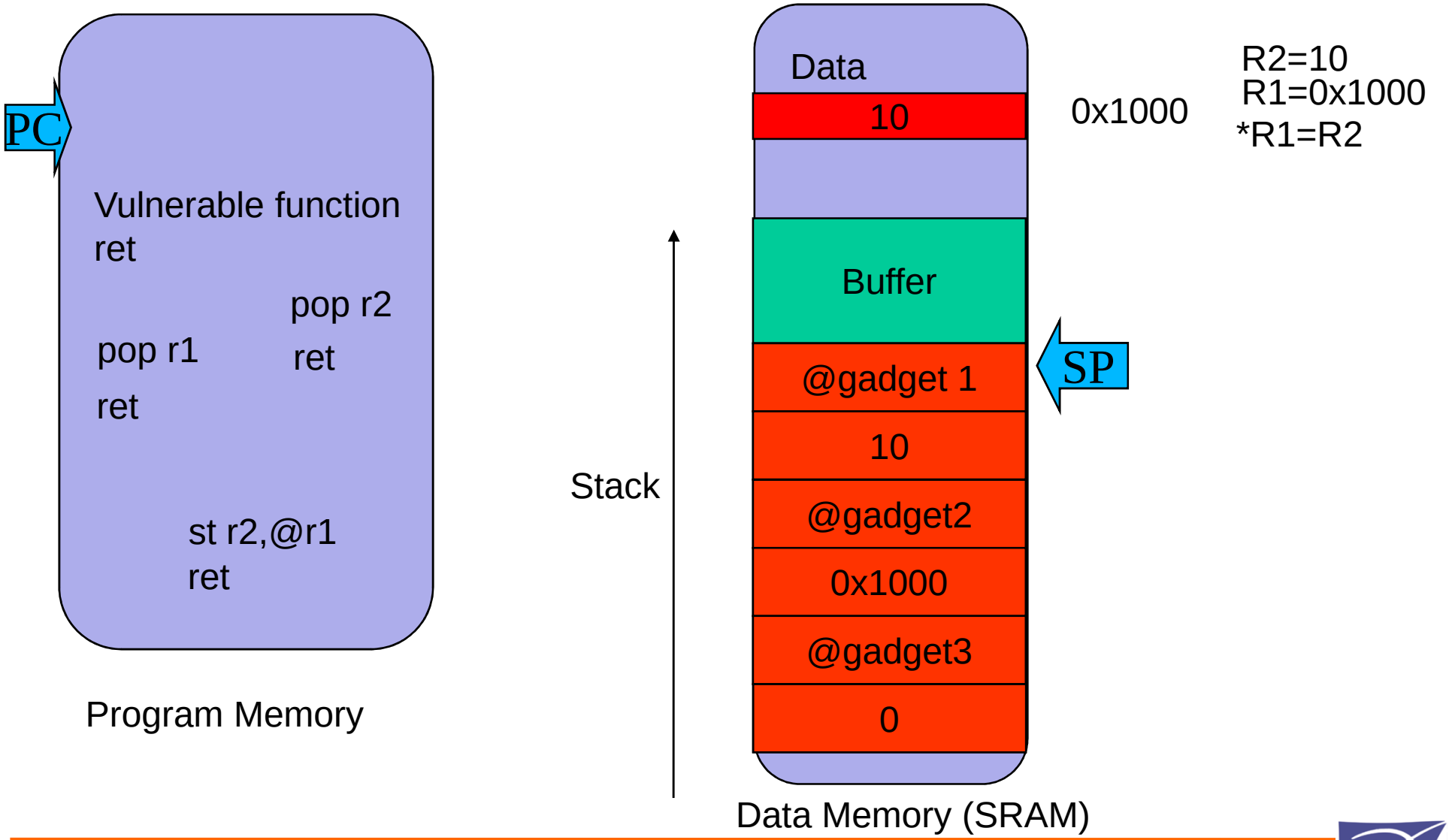


Illustration (3)

- A specially-crafted packet (that contains the second byte of the fake stack) is sent

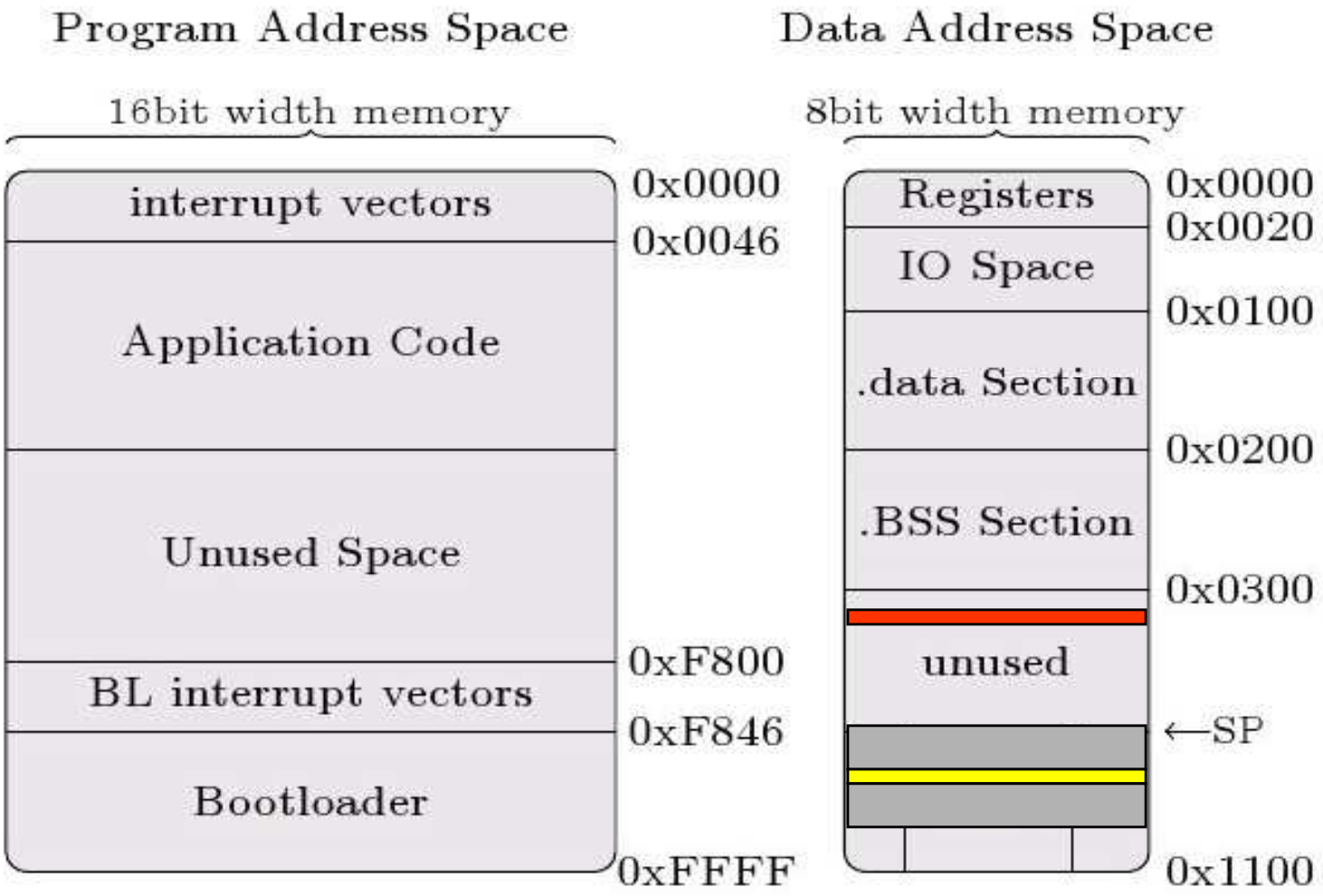


Illustration (4)

- This packet triggers a buffer overflow that copies its fake stack byte into the RAM memory… and reboots the node

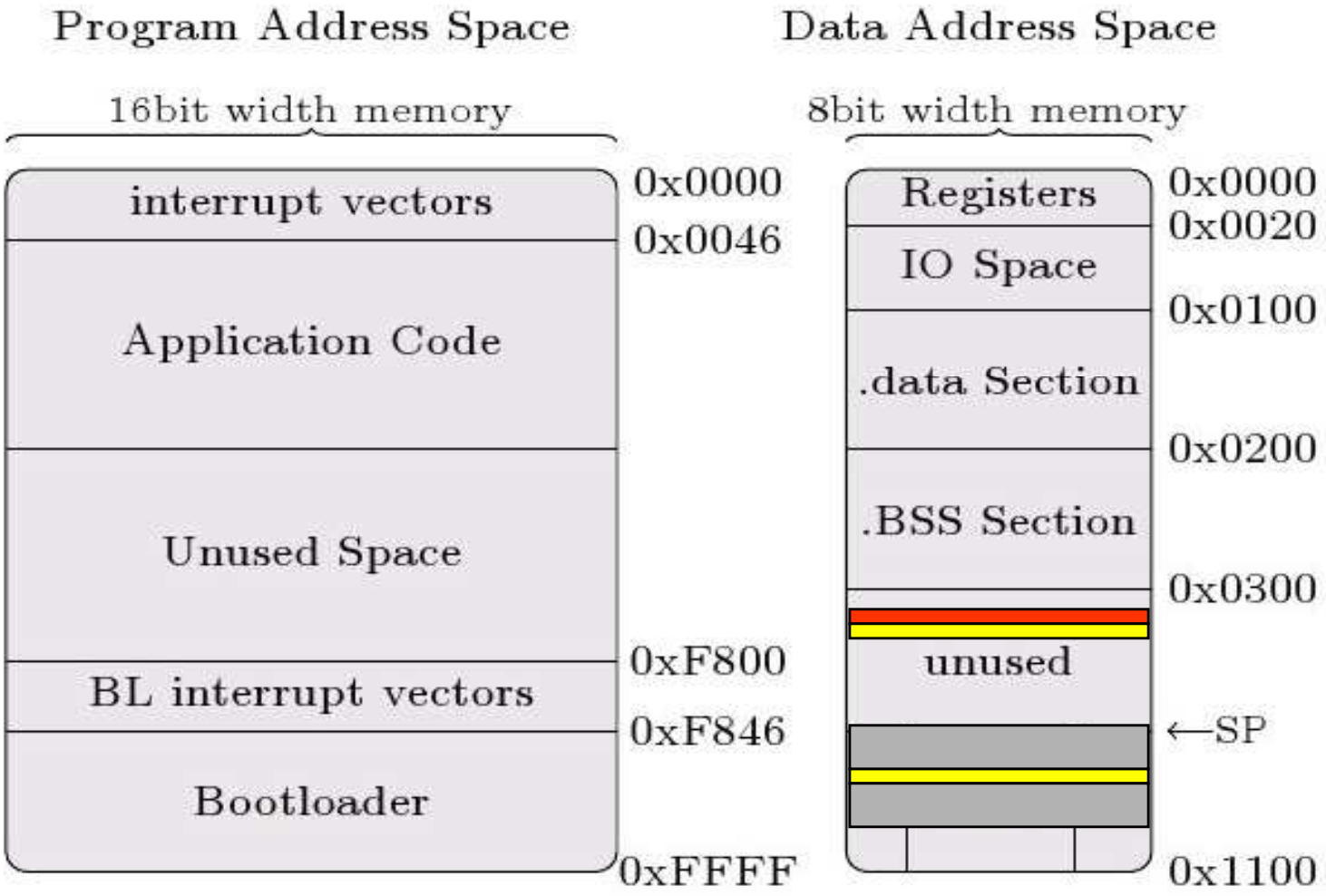


Illustration (5)

- After N packets the fake stack is in memory!

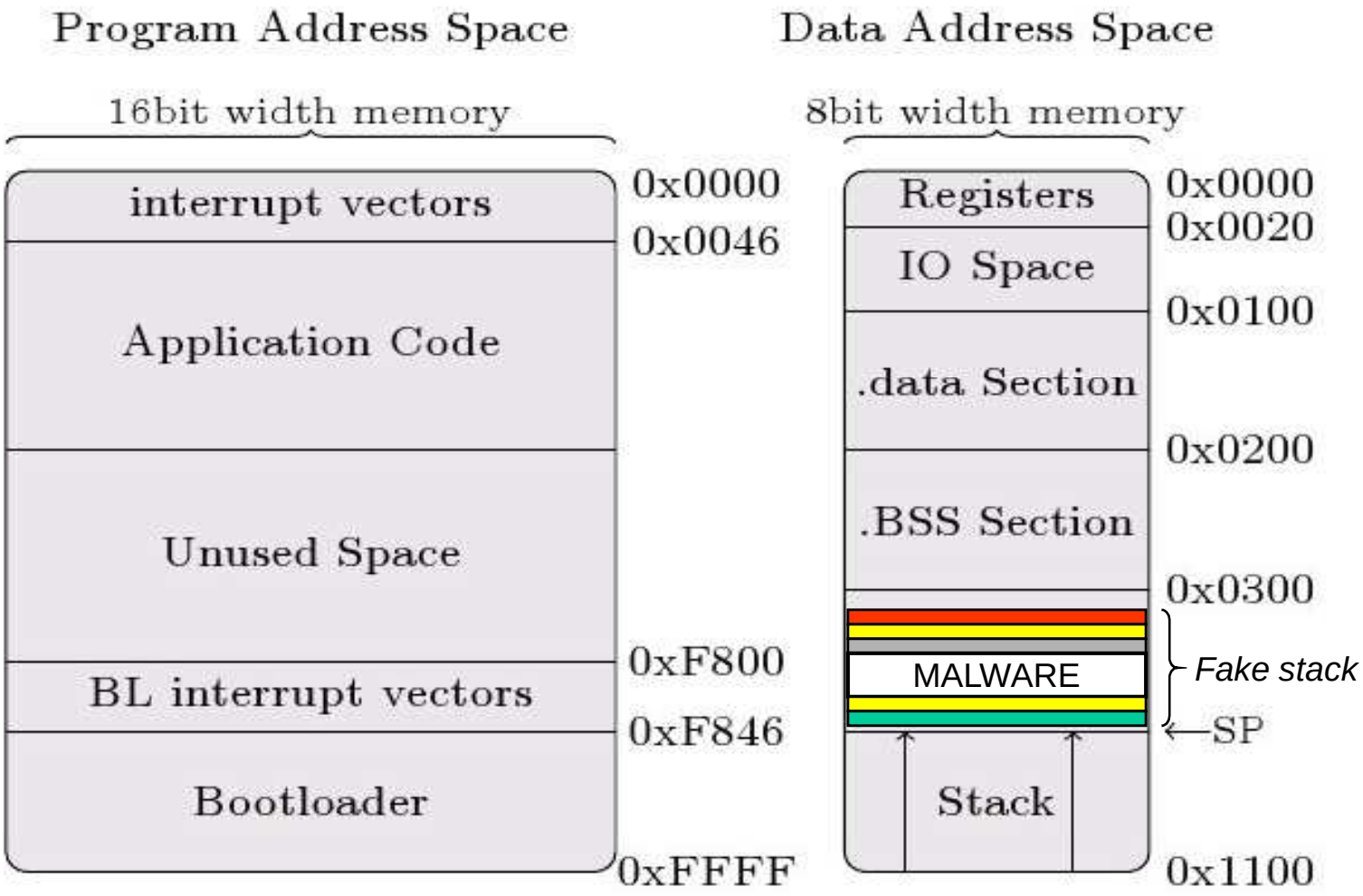


Illustration (6)

- A final specially-crafted packet is sent…

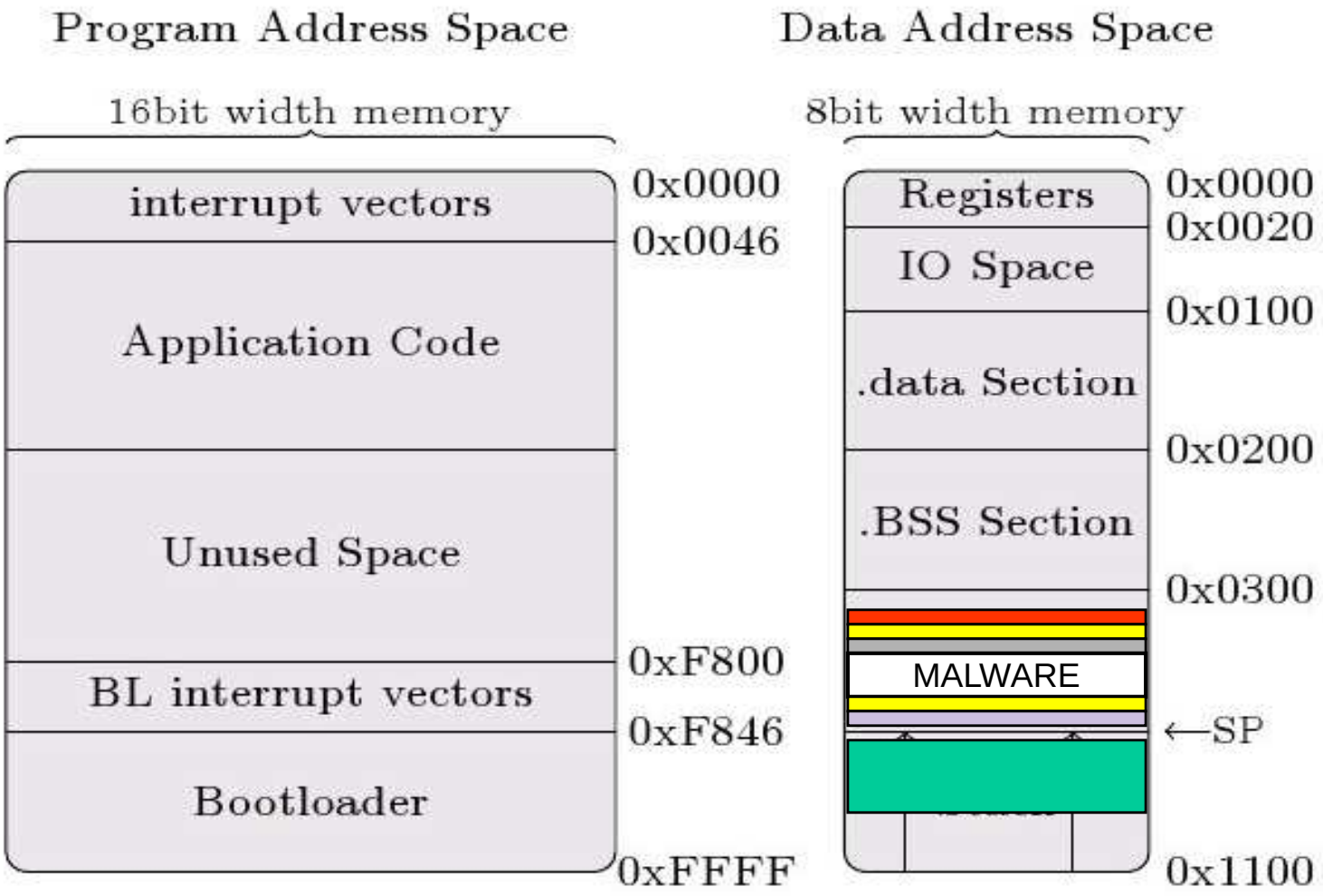


Illustration (7)

- …that triggers a buffer overflow and changes the SP to the fake stack

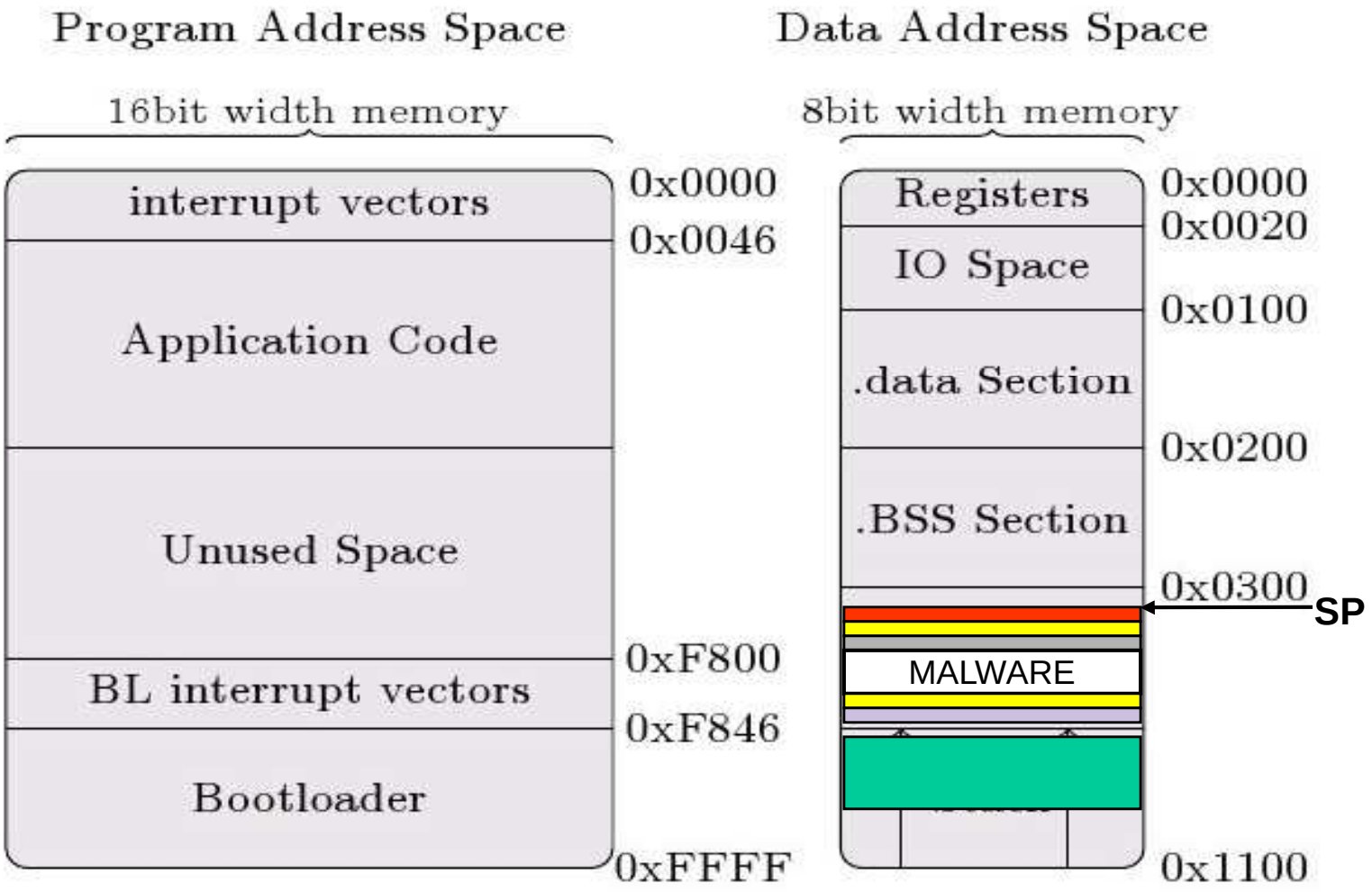


Illustration (8)

- The fake stack is then “executed” / interpreted

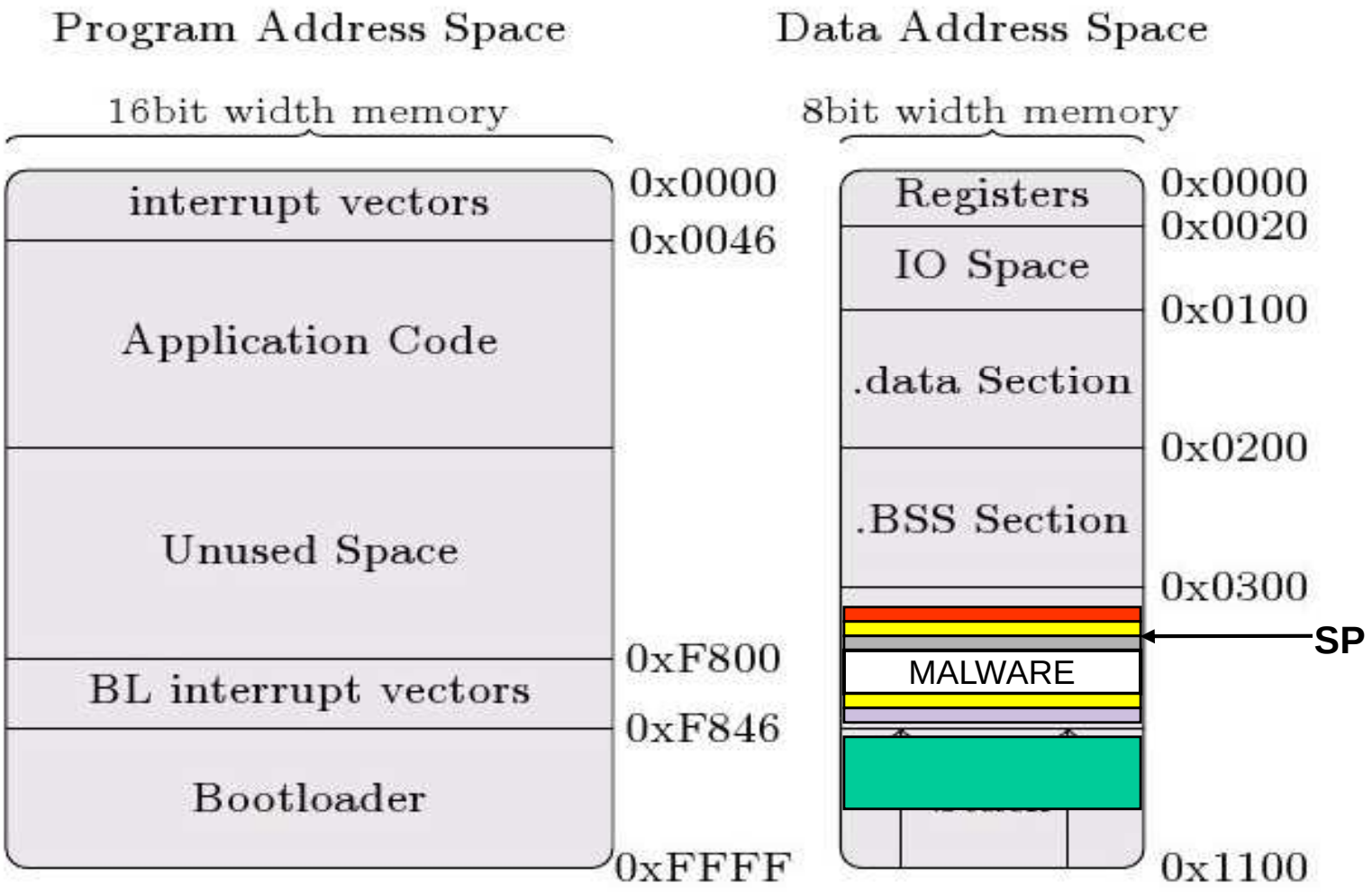
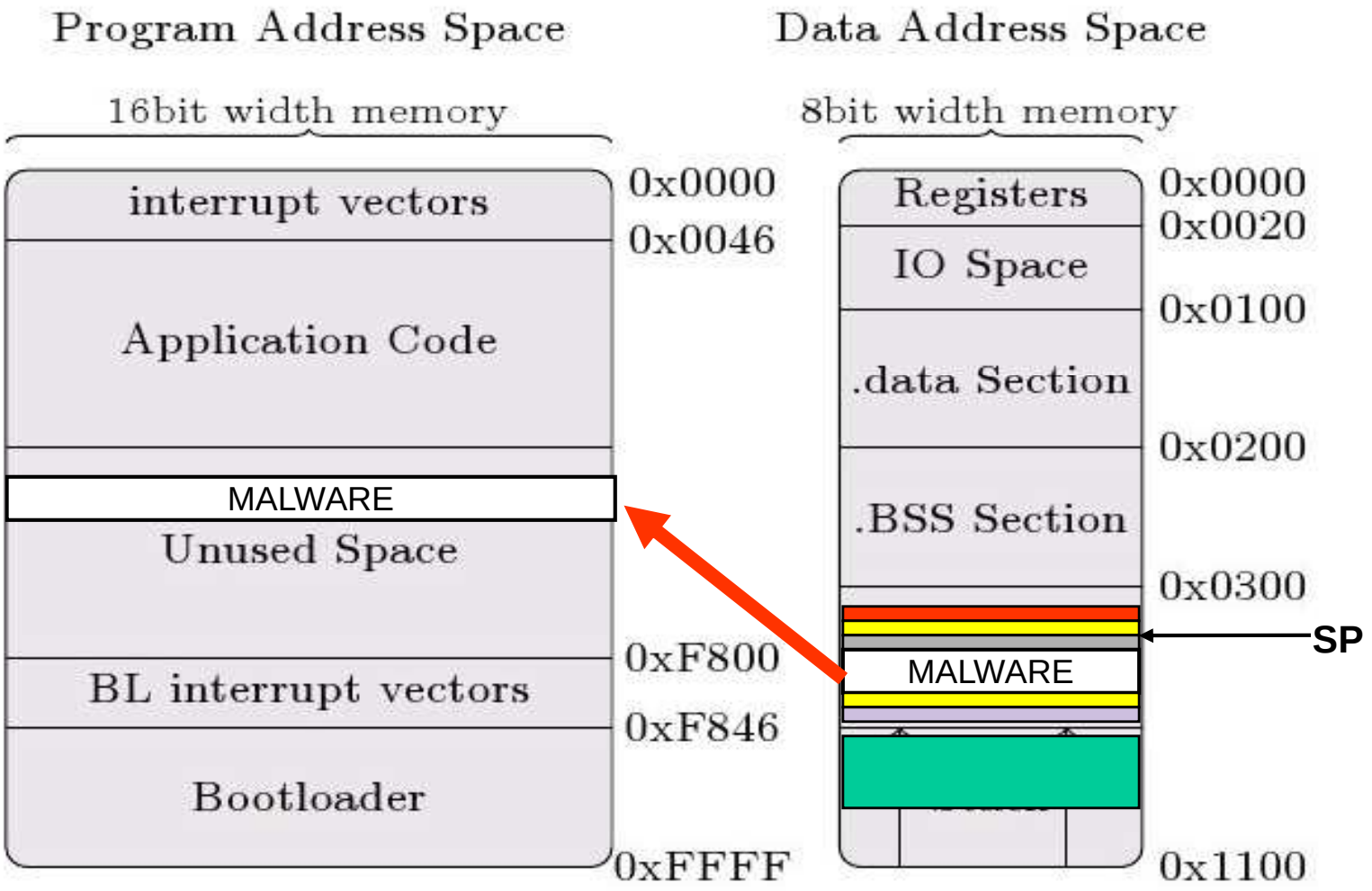


Illustration (9)

- The malware is copied from RAM to FLASH



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Main Results

- Harvard Architecture does not prevent code injection
- Return Oriented Programming can be used on constrained platforms
  - For a limited set of “actions”
- We showed that ROP can be used to inject code on AVR cpu
  - With small program size
  - Validated on 10 TinyOS applications
- The attack can be automated
  - We designed a tool that builds data injection payload automatically
- Worms and Viruses are realistic threats to Wireless sensor networks

Future work

Improving the attack

- Current attack uses gadgets on the Program memory
  - They are sub-optimal
    - Can only copy 1 byte into data memory per packet
- We propose to optimize the attack:
  - Injecting an optimized gadget
    - Using described attack
  - Injecting malware using this optimized gadget
    - Can copy Several bytes into data memory per packet
    - reduced number of packets necessary,
    - less reboots,
    - Less risks of packet lost

Counter measures

Existing Counter measures:

- Safe TinyOS
  - very promising but not a “silver bullet”
  - Manual source code annotation
  - Coding errors still possible

Possible Counter Measures:

- Binary Randomisation
  - too Small address space ?
- Random stack canaries?
  - Would make stack based buffer overflow more difficult
- Erase whole data memory between reboots
  - Reboots are not required

Questions ?