启发式检测之外,还对触发检测的时机进行了有效选择——基于敏感系统调用触发异常检测,从而很好地控制了性能开销.但这些代码重用攻击检测方案仅针对大多数通用的攻击有效,对于针对性攻击,基于启发式的检测方法还是存在被绕过的可能,例如,Isomeron,Size Does Matter 等研究中均给出了对此类启发式检测方法的bypass 实例[74,79].

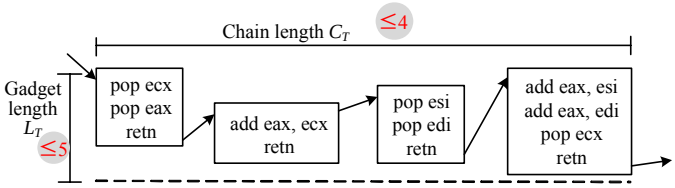


Fig.6 A heuristic detection strategy for code reuse attacks

图 6 基于启发式的代码重用攻击检测方法

3.2.2 栈异常

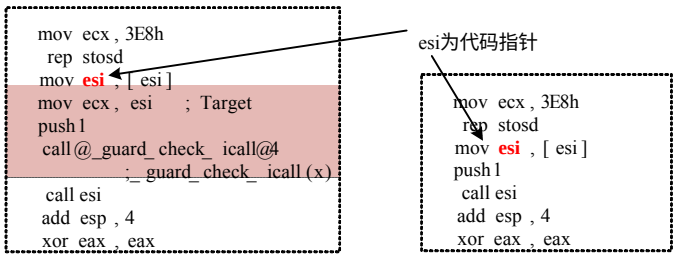
线程栈在程序函数调用过程中至关重要——保存了函数调用返回地址.利用线程栈的栈式结构,可以很容易地在栈上布局数据和程序跳转目标,实现 gadget 和函数的连续调用.为了方便布局攻击数据、尽可能地减小栈的破坏程度,攻击者通常会使用 stack pivot 指令将栈帧切换到一个位于堆上的伪造栈(forked stack)上.根据代码重用攻击过程中对栈或伪造栈的严重依赖性以及栈帧的异常切换,梁玉等人提出的 S-Tracker[80]和 Prakash[81]等人从栈完整性异常的角度对代码重用攻击进行检测.S-Tracker 对栈关键要素 esp,ebp 等进行了完整性定义,限制 esp 等指针的范围,在敏感行为发生时,触发对栈的检测;Prakash 等则是从代码重用中类似于 stack pivot 的关键 gadget 入手,使用 instrument 的方式对其修改,使得这类指令被调用时触发检测机制,通过判断栈指针完整性,实现对代码重用攻击的检测.

3.3 典型防护技术的实践与应用

对于防护方案,从理论、原型的提出到最终实际部署、应用是一个相对漫长的过程.近两年来,以 CFG 和 CET 为代表的基于控制流完整性的平台级防护方案在工业界得到应用和实践.

3.3.1 CFG

CFG(control flow guard)是微软对控制流完整性的一个平台级实现,通过代码编译和程序运行时(runtime)相结合的方式实现对 call 的间接跳转目标的限制,从而有效缓解包括代码重用在内的攻击方式.具体来说,微软在 Visual Studio 2015 中引入了 CFG,并通过代码生成选项"/guard:cf"开启对间接跳转指令的插桩.图 7 给出了插桩前后的对比.自 Windows 10 开始,微软正式引入了操作系统级的 CFG 支持.图 7(a)中额外调用的 _guard_check_ icall 在支持 CFG 的操作系统上,会通过调用 ntdll!LdrpVaildateUserCallTarget 对跳转目标进行验证;在不支持 CFG 的系统中是一个空调用,不引发额外的操作.操作系统通过位图 CFGBitmap 存储了当前调用的有效跳转目标集合,在 ntdll!LdrpValidateUserCallTarget 当中首先获取 CFGBitmap 对象,然后索引到对应的值,从而判断当前跳转是否有效:如果无效,则终止进程[82,83].



(a) 开启cfg (b) 未开启cfg

Fig.7 Comparison of code blocks generated by Visual Studio with CFG on and off

图 7 Visual Studio 开启 CFG 前后生成的代码对比

3.3.2 CET

2016 年 6 月,Intel 发布了称为 Control-flow Enforcement Technology(CET)的技术预览白皮书,正式公开了其准备推出的主要用于防护 ROP,COP/JOP(call/jump oriented programming)的芯片级解决方案.该方案的核心思想源自学术界早先提出的 shadow stack,即在系统中的特定内存区域构造一个专门用来存储间接跳转数据的栈[47,84].具体来说,当一个子函数被调用时,像传统方式一样,其返回地址将会被保存到线程栈上;同时也会被保存到 shadow stack 上;在程序后续执行中若遇到返回指令,则处理器需要保证线程栈上的返回地址与影子栈中的地址相匹配.如果二者不匹配,处理器则会抛出异常,使得操作系统能够捕获该异常并停止程序执行.

在 CET 技术中,Intel 从 CPU 级别对 shadow stack 提供了安全特性支持.Shadow stack 仅用于控制流转移操作,其中保存了函数返回地址等,与一般的数据栈相对独立.为了防止 shadow stack 被篡改,Intel 通过 CPU 的内存管理单元 MMU 在页表保护中提供了新的扩展属性,使得页内存除了具备读、写、执行保护外,还可被标记为 shadow stack 页.被标记为 shadow stack 的内存页,普通软件和指令无法直接对其进行写操作,只有通过特定的控制流转移指令和 Intel 提供的专门的 shadow stack 操作指令,才能实现对 shadow stack 的写操作,从而从硬件体系结构提供了 shadow stack 这一安全特性.

此外,Intel 还提供了一个新寄存器 SSP(shadow stack pointer).该寄存器始终指向 shadow stack 栈顶.当 CET 功能打开时,执行函数返回指令时,CPU 将自动地从 SSP 寄存器指向的 shadow stack 栈顶处取保存的返回地址,并与普通栈中的返回地址进行对比:二者如果不一致,CPU 则抛出异常,操作系统捕获该异常后进行后续处理.

和 CFG 一样,CET 技术也需要通过平台支撑才能完全实现防护效果.Intel 为 CET 技术提供了新指令 ENDBRANCH,该指令可用于标记合法的间接跳转目标.只有开发者使用支持 CET 技术的编译器来生成目标程序,才会使得目标程序中的返回地址等合法间接跳转目标被 ENDBRANCH 标记.在程序运行时,CPU 内部构建了一个状态机来跟踪 call/jmp 等间接跳转指令:当执行到 call/jmp 时,状态机由 IDLE 进入 WAIT_FOR_ENDBRANCH 状态.该状态下,其下一条指令必须是 ENDBRANCH:如果不是 ENDBRANCH,则说明跳转目标是非法的,触发 CET 保护,抛出异常;如果是 ENDBRANCH,则状态机再次进入 IDLE 状态.通过上述方式,实现对基于 COP/JOP 等代码重用方式的防护.

完善的防护方案需要构建从整个生态系统出发,尽可能地减少攻击面,提升安全性.CFG 和 CET 的设计和实施过程中,都是从底层硬件支撑、系统层程序执行环境保障、编译器层程序代码生成等环节进行了安全性和兼容性考虑,使其可快速地、最大化地被实际部署.但是,考虑到提供 CET 的 Intel 芯片目前尚未发布,且攻防对抗是一个持续、演进的过程,新的攻击方法存在绕过 CET,CFG 这类防护策略的可能性,所以二进制代码重用技术仍然是软件安全领域所面临的一个重要威胁.

4 总结与展望

代码重用作为一种程序执行方式,以其灵活的代码组织方式、功能逻辑动态生成的特点,在过去被广泛用于漏洞攻击当中.严峻的网络空间安全形势使得代码重用技术的研究价值凸显,学术界、工业界的研究人员在近 10 年中,从攻击和防护两个方面开展了深入的研究.本文前面部分重点对已有研究的分析和总结,一方面探讨了代码重用技术在攻击过程中的关键要素、逻辑组织方式及其攻防博弈下的演变历程;另一方面,从防护和缓解攻击的角度分析了已有防御技术的思路,如基于控制流完整性的防护思路和基于随机化的防护思路.此外,文中也对最新的来自工业界防护方法 CFG,CET 进行了分析,为研究实用性更强的防护技术提供了启发.

代码重用技术除了用于攻击之外,这种动态生成程序逻辑的程序执行方式亦可用于代码混淆,尤其是对关键功能、关键逻辑的代码混淆和隐藏[85,86].例如,在程序运行过程中,通过服务器推送的特定数据输入,动态生成所需要的功能逻辑,实现关键功能执行.这种方式的一个关键是在正常程序中构建一个风险可控的“漏洞”,使得程序控制流有机会被隐藏的功能逻辑使用.因此,研究如何利用基于二进制代码重用的程序执行方式进行代码逻辑混淆、代码隐写等应用,是一项可探索的工作.

随着防御技术的不断演进,代码重用攻击不局限于编译、发布的程序,可能更加倾向于动态生成代码的重

用.目前,针对 JIT 等方式动态生成的二进制代码的防护相对薄弱,这将成为攻击者的新的攻击面.因此,针对动态生成代码的攻击防护,也就是代码重用攻击对抗中的一个新的战场.

此外,从控制流完整性和随机化的角度研究代码重用攻击防御方法仍将继续.在控制流完整性防护方面,一方面是完善已有的防御方法,如 CET,CFG,使其更加完备;另一方面,继续探索如何高效地实现更细粒度的 CFI.对于随机化能力增强的研究可从 3 个方面展开:(1) 引入新的随机化机制,弥补现有随机化机制中的不足;(2) 对内存中不同的数据对象进行不同程度的随机化,除了使其具备防范代码重用攻击之外,还可提升其整体安全性;(3) 提高随机化的熵,增强随机化的效果.此外,邬江兴院士提出的拟态计算机理论则是从整个计算机体系结构出发,提高运行环境或执行机构的不确定性[87].对于该理论,从攻击者的角度来看,一类与运行环境、执行程序实体关系紧密的攻击方式将可能失效.因此,研究新的计算机体系、从根源上解决代码重用等众多内存漏洞攻击,也是可供探索的方向.

典型代码重用攻击需要配合内存信息泄漏,而这其中的信息泄露既包括程序漏洞引发的内存任意读缺陷,也包括由软件、硬件设计缺陷导致的侧信道信息泄露.因此,如何从硬件、系统、软件等层面有效防止程序运行信息泄漏、防止内存中敏感数据泄漏,是近期研究的一个方向.在数据中心、云环境中,针对硬件特性引发的侧信道信息泄露的研究也值得关注.

二进制代码重用在当前的计算机系统体系结构和软件生态环境下暂时无法消除,基于代码重用的攻防博弈仍将继续.因此,无论是为了在网络空间安全博弈中占据主动权,还是出于防护的目的,都有必要对二进制代码重用技术做进一步的研究.

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