MP2_report 組員與分工 組員: 林群佑, 刁一平 工作項目 分工 林群佑 Trace Code 功能實作與除錯 刁一平 Trace code Kernel::Kernel() In []: Kernel::Kernel(int argc, char **argv) { randomSlice = FALSE; debugUserProg = FALSE; execExit = FALSE; consoleIn = NULL; // default is stdin consoleOut = NULL; // default is stdout #ifndef FILESYS STUB formatFlag = FALSE; reliability = 1; // network reliability, default is 1.0 hostName = 0; // machine id, also UNIX socket name // 0 is the default machine id for (int i = 1; i < argc; i++) {</pre> if (strcmp(argv[i], "-rs") == 0) { //-rs <randomSeed>: 設置隨機種子,用於初始化偽隨機數生成器 ASSERT(i + 1 < argc); RandomInit(atoi(argv[i + 1])); // initialize pseudo-random // number generator randomSlice = TRUE; i**++**; } **else if** (strcmp(argv[i], "-s") == 0) { //-s: 啟用用戶程序的調試模式 debugUserProg = TRUE; } **else if** (strcmp(argv[i], "-e") == 0) { //-e <execfile>:指定執行檔案 execfile[++execfileNum] = argv[++i]; cout << execfile[execfileNum] << "\n";</pre> } **else if** (strcmp(argv[i], "-ee") **==** 0) { **//-**ee:設置在所有執行緒完成後結束程式 // Added by @dasbd72 // To end the program after all the threads are done execExit = TRUE; } **else if** (strcmp(argv[i], "-ci") == 0) { //-ci <consoleIn>:設置自定義的輸入來源 ASSERT(i + 1 < argc); consoleIn = argv[i + 1]; } **else if** (strcmp(argv[i], "-co") == 0) { //-co <consoleOut>:設置自定義的輸出地方 ASSERT(i + 1 < argc); consoleOut = argv[i + 1]; i**++;** } else if (strcmp(argv[i], "-f") == 0) { //-f (僅在非 FILESYS_STUB 下可用):設置文件系統格式化標誌 formatFlag = TRUE; #endif } else if (strcmp(argv[i], "-n") == 0) { //-n <reliability>:設置網路可靠性 ASSERT(i + 1 < argc); // next argument is float reliability = atof(argv[i + 1]); } **else if** (strcmp(argv[i], "-m") == 0) { //-m <hostName>:設置主機名稱 ASSERT(i + 1 < argc); // next argument is int hostName = atoi(argv[i + 1]); } **else if** (strcmp(argv[i], "-u") == 0) { //-u:顯示使用說明 cout << "Partial usage: nachos [-rs randomSeed]\n";</pre> cout << "Partial usage: nachos [-s]\n";</pre> cout << "Partial usage: nachos [-ci consoleIn] [-co consoleOut]\n";</pre> #ifndef FILESYS_STUB cout << "Partial usage: nachos [-nf]\n";</pre> #endif cout << "Partial usage: nachos [-n #] [-m #]\n";</pre> 進到 threads/kernel.cc 觀察 Kernel() 函式 這是用來解析使用者輸入的指令的函式,預設 randomSlice=FALSE, debugUserProg=FALSE, execExit=FALSE, consoleIn=NULL, consoleOut=NULL, 可以在檔案名稱後加上不同指令來改變其值(各種功能設定) 下方是按照函式使用的流程寫的(從 Kernel::ExecAll() 開始) Kernel::ExecAll() In []: void Kernel::ExecAll() { for (int i = 1; i <= execfileNum; i++) {</pre> int a = Exec(execfile[i]); currentThread->Finish(); // Kernel::Exec(); 進到 threads/thread.cc 從 Kernel::ExecAll() 開始 這個就是將所有待辦的程式放入執行(呼叫 Exec() 函式),執行完後呼叫 currentThread->Finish() 來表示完成所有待辦程式 Kernel::Exec() In []: int Kernel::Exec(char *name) { t[threadNum] = new Thread(name, threadNum); t[threadNum] -> setIsExec(); t[threadNum] -> space = new AddrSpace(); t[threadNum] -> Fork((VoidFunctionPtr)&ForkExecute, (void *)t[threadNum]); threadNum++; return threadNum - 1; cout << "Total threads number is " << execfileNum << endl;</pre> for (int n=1;n<=execfileNum;n++) {</pre> t[n] = new Thread(execfile[n]); t[n]->space = new AddrSpace(); t[n]->Fork((VoidFunctionPtr) &ForkExecute, (void *)t[n]); cout << "Thread " << execfile[n] << " is executing." << endl;</pre> cout << "debug Kernel::Run finished.\n";</pre> // Thread *t1 = new Thread(execfile[1]); // Thread *t1 = new Thread("../test/test1"); // Thread *t2 = new Thread("../test/test2"); // AddrSpace *halt = new AddrSpace(); // t1->space = new AddrSpace(); // t2->space = new AddrSpace(); // halt->Execute("../test/halt"); // t1->Fork((VoidFunctionPtr) &ForkExecute, (void *)t1); // t2->Fork((VoidFunctionPtr) &ForkExecute, (void *)t2); // currentThread->Finish(); // Kernel::Run(); // cout << "after ThreadedKernel:Run();" << endl; // unreachable</pre> 進到 threads/kernel.cc 觀察 Exec() 具體執行什麼 首先建立一個 Process Control Block (在這裡我們可以看到 NachOS 中使用 Thread 這個物件作為 Process Control Block)然後呼叫 setIsExec() ,接著分配空間(呼叫 new AddrSpace() 建立一個 AddrSpace 物件用來管理記憶體),再呼叫 Fork() ,最後將 threadNum 用來記錄有多少 個 Process Control Block 的變數加一 Thread::setIsExec() In []: void setIsExec() { this->isExec = true; } 就只是將當前 Process Control Block (this)的 isExec 變數設為 true 代表正在處理 AddrSpace::AddrSpace() In []: AddrSpace::AddrSpace() { pageTable = new TranslationEntry[NumPhysPages]; for (int i = 0; i < NumPhysPages; i++) {</pre> pageTable[i].virtualPage = i; // for now, virt page # = phys page # pageTable[i].physicalPage = i; pageTable[i].valid = TRUE; pageTable[i].use = FALSE; pageTable[i].dirty = FALSE; pageTable[i].readOnly = FALSE; // zero out the entire address space bzero(kernel->machine->mainMemory, MemorySize); 接著進到 userprog/addrspace.cc 觀察 AddrSpace() 這個函式會將 pageTable 這個變數設為對應映射到的實體位置(目前上面程式碼為未實作完成的狀態),接著初始化 pageTable 內的各種變數,最後將整個空間設為 0 清理掉所有可能是其他程式遺留下的資料 Thread::Fork() In []: void Thread::Fork(VoidFunctionPtr func, void *arg) { Interrupt *interrupt = kernel->interrupt; Scheduler *scheduler = kernel->scheduler; IntStatus oldLevel; DEBUG(dbgThread, "Forking thread: " << name << " f(a): " << (int)func << " " << arg); StackAllocate(func, arg); oldLevel = interrupt->SetLevel(IntOff); scheduler->ReadyToRun(this); // ReadyToRun assumes that interrupts // are disabled! (void) interrupt->SetLevel (oldLevel); 進到 threads/thread.cc 觀察 Fork() 函式 這個函式會呼叫 StackAllocate() 分配 stack 的空間,然後關閉 interrupt 的功能,接著讓 scheduler 知道這個 Process control Block 的程式是準備好執行的(呼叫 scheduler->ReadyToRun(this)),就是已經將要執行的程式與變數放入 stack 中,最後再回到原本的 interrupt level Thread::StackAllocate() In []: void Thread::StackAllocate(VoidFunctionPtr func, void *arg) { stack = (int *)AllocBoundedArray(StackSize * sizeof(int)); #ifdef PARISC // HP stack works **from** low addresses to high addresses // everyone **else** works the other way: **from** high addresses to low addresses stackTop = stack + 16; // HP requires 64-byte frame marker stack[StackSize - 1] = STACK_FENCEPOST; #endif #ifdef SPARC stackTop = stack + StackSize - 96; // SPARC stack must contains at // least 1 activation record // to start with. *stack = STACK_FENCEPOST; #endif #ifdef PowerPC // RS6000 stackTop = stack + StackSize - 16; // RS6000 requires 64-byte frame marker *stack = STACK_FENCEPOST; #endif #ifdef DECMIPS stackTop = stack + StackSize - 4; // -4 to be on the safe side! *stack = STACK_FENCEPOST; #endif #ifdef ALPHA stackTop = stack + StackSize - 8; // -8 to be on the safe side!*stack = STACK_FENCEPOST; #endif #ifdef x86 // the x86 passes the **return** address on the stack. In order **for** SWITCH() // to go to ThreadRoot when we switch to this thread, the **return** addres // used in SWITCH() must be the starting address of ThreadRoot. stackTop = stack + StackSize - 4; // -4 to be on the safe side! *(--stackTop) = (int)ThreadRoot; *stack = STACK_FENCEPOST; #endif #ifdef PARISC machineState[PCState] = PLabelToAddr(ThreadRoot); machineState[StartupPCState] = PLabelToAddr(ThreadBegin); machineState[InitialPCState] = PLabelToAddr(func); machineState[InitialArgState] = arg; machineState[WhenDonePCState] = PLabelToAddr(ThreadFinish); #else machineState[PCState] = (void *)ThreadRoot; machineState[StartupPCState] = (void *)ThreadBegin; machineState[InitialPCState] = (void *)func; machineState[InitialArgState] = (void *)arg; machineState[WhenDonePCState] = (void *)ThreadFinish; #endif 進到 threads/thread.cc 觀察 StackAllocate() 函式 這個函式就是呼叫 AllocBoundedArray() 分配空間給 stack 和初始化 stack ,而 stack top 需針對不同作業系統有不同處理 Kernel::ForkExecute In []: void ForkExecute(Thread *t) { if (!t->space->Load(t->getName())) { return; // executable not found t->space->Execute(t->getName()); 進到 threads/kernel.cc 觀察 ForkExecute() 函式 這個函式是在 Kernel::Exec() 中被 Thread::Fork() 放入 stack 中具體要執行的函式,這個功能就是載入指定的程式(呼叫 t->space->Load()),如果成功那就執行(呼叫 t->space->Execute()) AddrSpace::Load() In []: bool AddrSpace::Load(char *fileName) { OpenFile *executable = kernel->fileSystem->Open(fileName); NoffHeader noffH; unsigned int size; if (executable == NULL) { cerr << "Unable to open file " << fileName << "\n";</pre> return FALSE; executable->ReadAt((char *)&noffH, sizeof(noffH), 0); if ((noffH.noffMagic != NOFFMAGIC) && (WordToHost(noffH.noffMagic) == NOFFMAGIC)) SwapHeader(&noffH); ASSERT(noffH.noffMagic == NOFFMAGIC); #ifdef RDATA // how big is address space? size = noffH.code.size + noffH.readonlyData.size + noffH.initData.size + noffH.uninitData.size + UserStackSize; // we need to increase the size // to leave room **for** the stack #else // how big is address space? size = noffH.code.size + noffH.initData.size + noffH.uninitData.size + UserStackSize; // we need to increase the size // to leave room for the stack #endif numPages = divRoundUp(size, PageSize); size = numPages * PageSize; ASSERT(numPages <= NumPhysPages); // check we're not trying // to run anything too big --// at least until we have // virtual memory DEBUG(dbgAddr, "Initializing address space: " << numPages << ", " << size); // then, copy in the code and data segments into memory // Note: this code assumes that virtual address = physical address if (noffH.code.size > 0) { DEBUG(dbgAddr, "Initializing code segment."); DEBUG(dbgAddr, noffH.code.virtualAddr << ", " << noffH.code.size);</pre> executable->ReadAt(&(kernel->machine->mainMemory[noffH.code.virtualAddr]), noffH.code.size, noffH.code.inFileAddr); if (noffH.initData.size > 0) { DEBUG(dbgAddr, "Initializing data segment."); DEBUG(dbgAddr, noffH.initData.virtualAddr << ", " << noffH.initData.size);</pre> executable->ReadAt(&(kernel->machine->mainMemory[noffH.initData.virtualAddr]), noffH.initData.size, noffH.initData.inFileAddr); #ifdef RDATA if (noffH.readonlyData.size > 0) { DEBUG(dbgAddr, "Initializing read only data segment."); DEBUG(dbgAddr, noffH.readonlyData.virtualAddr << ", " << noffH.readonlyData.size);</pre> executable->ReadAt(&(kernel->machine->mainMemory[noffH.readonlyData.virtualAddr]), noffH.readonlyData.size, noffH.readonlyData.inFileAddr); #endif delete executable; // close file return TRUE; // success 進到 userprog/addrspace.cc 觀察 Load() 函式 首先會打開程式指定的檔案,如果失敗則回傳 FALSE ,然後檢查 NOFF 格式是否合格,接著計算程式所需記憶體空間,並檢查是否有足夠空間執行程式,若有則將程式及資料片段複製進記憶體對應空間,最後關閉檔案並返回 TRUE 代表成功載入資料,而本次作業的實作就在這裡完 成虛擬記憶體位置與物理記憶體位置的映射表(目前上方程式碼為未實作的狀態) AddrSpace::Execute() In []: void AddrSpace::Execute(char *fileName) { kernel->currentThread->space = this; this->InitRegisters(); // set the initial register values this->RestoreState(); // load page table register kernel->machine->Run(); // jump to the user progam ASSERTNOTREACHED(); // machine->Run never returns; // the address space exits // by doing the syscall "exit" 進到 userprog/addrspace.cc 觀察 Execute() 函式 首先,指定當前執行緒要載入的資料在哪(記錄在 Process Control Block (this)中),然後初始化暫存器,接著載入 page table 然後執行,如果沒能執行程式則報錯 Machine::Run() In []: void Machine::Run() { Instruction *instr = new Instruction; // storage for decoded instruction if (debug->IsEnabled('m')) { cout << "Starting program in thread: " << kernel->currentThread->getName(); cout << ", at time: " << kernel->stats->totalTicks << "\n";</pre> kernel->interrupt->setStatus(UserMode); DEBUG(dbgTraCode, "In Machine::Run(), into OneInstruction " << "== Tick " << kernel->stats->totalTicks << " ==");</pre> OneInstruction(instr); DEBUG(dbgTraCode, "In Machine::Run(), return from OneInstruction " << "== Tick " << kernel->stats->totalTicks << " ==");</pre> DEBUG(dbgTraCode, "In Machine::Run(), into OneTick " << "== Tick " << kernel->stats->totalTicks << " ==");</pre> kernel->interrupt->OneTick(); DEBUG(dbgTraCode, "In Machine::Run(), return from OneTick " << "== Tick " << kernel->stats->totalTicks << " ==");</pre> if (singleStep && (runUntilTime <= kernel->stats->totalTicks)) Debugger(); 進到 machine/mipssim.cc 觀察 Run() 函式 這部分檢查有哪些指令輸入,模擬程式執行的解碼過程 instr 就是 User Program 的某一行程式碼 OneTick() 就是模擬 CPU Clock 往前跑的情形,通常一條指令假設會讓系統前進一個 Clock cycle Scheduler::ReadyToRun() In []: void Scheduler::ReadyToRun(Thread *thread) { ASSERT(kernel->interrupt->getLevel() == IntOff);//檢查 interrupt 功能是否已經關閉中斷,若無則報錯 DEBUG(dbgThread, "Putting thread on ready list: " << thread->getName()); // cout << "Putting thread on ready list: " << thread->getName() << endl ;</pre> thread->setStatus(READY); readyList->Append(thread); 進到 threads/scheduler.cc 觀察 ReadyToRun() 函式 這個函式就是將 Process Control Block (thread)的 setStatus 變數設為 READY ,然後將這個 Process Control Block (thread)放入 readyList Thread::Finish() In []: void Thread::Finish() { (void) kernel->interrupt->SetLevel(IntOff); ASSERT (this == kernel->currentThread); DEBUG(dbgThread, "Finishing thread: " << name);</pre> if (kernel->execExit && this->getIsExec()) { kernel->execRunningNum--; if (kernel->execRunningNum == 0) { kernel->interrupt->Halt(); Sleep(TRUE); // invokes SWITCH // not reached 進到 threads/thread.cc 觀察 Finish() 函式 首先先關閉 interrupt 功能,然後檢查是否所有執行緒已經停止以及當前程式是否完成,當所有執行緒已經停止且當前執行緒工作完成則將紀錄有多少程式在運行的變數減一,當變數為0時,代表已經沒有任何 process 在執行,此時便呼叫 kernel->interrupt->Halt() 結束 NachOS 運作, 而若還有 process 在運作則呼叫 Sleep(TRUE) ,代表當前執行緒進入休息狀態 thread::Sleep() In []: void Thread::Sleep(bool finishing) { Thread *nextThread; ASSERT(this == kernel->currentThread);//檢查現在的 thread 是否為 currentThread ,不是則報錯 ASSERT(kernel->interrupt->getLevel() == IntOff);//檢查 interrupt 功能是否已經關閉中斷,若無則報錯 DEBUG(dbgThread, "Sleeping thread: " << name);</pre> DEBUG(dbgTraCode, "In Thread::Sleep, Sleeping thread: " << name << ", " << kernel->stats->totalTicks); status = BLOCKED; // cout << "debug Thread::Sleep " << name << "wait for Idle\n";</pre> while ((nextThread = kernel->scheduler->FindNextToRun()) == NULL) { kernel->interrupt->Idle(); // no one to run, wait for an interrupt // returns when it's time for us to run kernel->scheduler->Run(nextThread, finishing); 進到 threads/thread.cc 觀察 Sleep() 函式 首先先將當前 Process Control Block (thread)狀態設為 BLOCKED 然後檢查是否還有其他任務,若無則進入空閒狀態,等待 interrupt,直到下個 Process Control Block 出現,當下個 Process Control Block 出現時呼叫 kernel->scheduler->Run() 執行下個 Program Scheduler::Run() In []: void Scheduler::Run(Thread *nextThread, bool finishing) { Thread *oldThread = kernel->currentThread; ASSERT(kernel->interrupt->getLevel() == IntOff);//檢查 interrupt 功能是否已經關閉中斷,若無則報錯 if (finishing) { // mark that we need to delete current thread ASSERT (toBeDestroyed == NULL); toBeDestroyed = oldThread; if (oldThread->space != NULL) { // if this thread is a user program, oldThread->SaveUserState(); // save the user's CPU registers oldThread->space->SaveState(); oldThread->CheckOverflow(); // check if the old thread // had an undetected stack overflow kernel->currentThread = nextThread; // switch to the next thread nextThread->setStatus(RUNNING); // nextThread is now running DEBUG(dbgThread, "Switching from: " << oldThread->getName() << " to: " << nextThread->getName()); // This is a machine-dependent assembly language routine defined // in switch.s. You may have to think // a bit to figure out what happens after this, both from the point // of view of the thread and from the perspective of the "outside world". SWITCH(oldThread, nextThread); // we're back, running oldThread // interrupts are off when we return from switch! ASSERT(kernel->interrupt->getLevel() == IntOff); DEBUG(dbgThread, "Now in thread: " << oldThread->getName()); CheckToBeDestroyed(); // check if thread we were running // before this one has finished // and needs to be cleaned up if (oldThread->space != NULL) { // if there is an address space oldThread->RestoreUserState(); // to restore, do it. oldThread->space->RestoreState(); 進到 threads/scheduler.cc 觀察 Run() 函式 首先查看當前 process 的 Process Control Block 中的 finish 變數檢查是否已完成,若已完成,則將其放入 toBeDestroyed 這樣之後便會刪除,接著,如果程式是 user program,則須將其資料儲存起來,接著檢查舊 process (oldThread)是否有 stack overflow ,然後將當前執行緒切 換到下一個 Process Control Block 的 process ,並將狀態設為 RUNNING ,再呼叫 SWITCH(oldThread, nextThread) 函式完成當前執行緒工作切換,完成交換後,呼叫 CheckToBeDestroyed() 來檢查是否有執行完成需要被回收掉的程式,最後檢查舊 Process Control Block (oldThread)是否還有資料(還未完成),如果有,將資料存回舊 Process Control Block (oldthread)讓執行緒回來執行 oldthread process 時能從 Process Control Block 中找到資料位置 Implement page table in NachOS To impelemet page tabe based on hint, we need the information of the number of remaining physical pages and the whether the page is use or not. In the addrspace class, two member variables were added: remain, which records the current number of available physical pages, and the bool array used, which tracks whether each physical page is in use, where TRUE indicates it is in use and FALSE indicates it is not. addrspace.h In []: static int remain; static bool used[]; Initialize the variables in addrspace.cc In []: bool AddrSpace::used[NumPhysPages] = {false}; int AddrSpace::reamin = NumPhysPages; For handelling exception, add MemoryLimitException before NumExceptionTypes in machine.h In []: enum ExceptionType { NoException, // Everything ok! SyscallException, // A program executed a system call. PageFaultException, // No valid translation found ReadOnlyException, // Write attempted to page marked // "read-only" BusErrorException, // Translation resulted in an // invalid physical address AddressErrorException, // Unaligned reference or one that // was beyond the end of the // address space OverflowException, // Integer overflow in add or sub. IllegalInstrException, // Unimplemented or reserved instr. MemoryLimitException, # 8 NumExceptionTypes Since we want to apply function call kernel->machine->RaiseException(), so we add friend class AddrSpace in the machine class in machine.h In []: friend class AddrSpace; AddrSpace::AddrSpace() In the constructor, since not load into the memory yet, so there is no corresponding physical page, thus I set every physicalPage into value -1 at first In []: AddrSpace::AddrSpace() { pageTable = new TranslationEntry[NumPhysPages]; for (int i = 0; i < NumPhysPages; i++) {</pre> pageTable[i].virtualPage = i; // for now, virt page # = phys page # pageTable[i].physicalPage = -1; # not loaded first pageTable[i].valid = TRUE; pageTable[i].use = FALSE; pageTable[i].dirty = FALSE; pageTable[i].readOnly = FALSE; # zero out the entire memory space bzero(kernel->machine->mainMemory, MemorySize); AddrSpace::~AddrSpace() By checking for each physical page if it is used, if so, then set it to FALSE, and add the remain page numbers for each release physical page In []: AddrSpace::~AddrSpace() { # Free the physical pages and release the page table for(unsigned int i = 0; i < NumPhysPages; i++) {</pre> int physPage = pageTable[i].physicalPage; if (physPage == -1) continue; AddrSpace::used[physPage] = FALSE; AddrSpace::remain++; delete pageTable; AddrSpace::Load First, it checks if the required numPages exceeds the available physical pages (remain). If it does, RaiseException() will be called with MemoryLimitException, indicating insufficient memory, and it will return FALSE to signify that the load has failed. If the required pages do not exceed the available pages, it will then begin searching for available physical pages one by one, needing to find a total of numPages. For each page found, used is set to TRUE to indicate it is in use, and remain is decreased accordingly if (numPages > AddrSpace::remain) { kernel->machine->RaiseException(MemoryLimitException, 0); return FALSE; int j = 0;for(unsigned int i = 0; i < numPages; i++) {</pre> for(j = 0; j < NumPhysPages; j++) {</pre> if(AddrSpace::used[j] == FALSE) break; pageTable[i].physicalPage = j; AddrSpace::used[j] = TRUE; AddrSpace::remain--; AddrSpace::Translate In []: ExceptionType AddrSpace::Translate(unsigned int vaddr, unsigned int *paddr, int isReadWrite) { TranslationEntry *pte; unsigned int vpn = vaddr / PageSize; unsigned int offset = vaddr % PageSize; pte = &pageTable[vpn]; pfn = pte->physicalPage; *paddr = pfn * PageSize + offset; return NoException; Based on the translate function in addrspace, we can get: physical address = pageTable[virtual/PageSize].physicalPage * PageSize + virtual % PageSize The calculation determines which page in the program's own page table the virtual address falls under and since pageTable[i].virtualPage = i, the corresponding page entry in the page table can be directly accessed through the virtual address. Then, it retrieves the physical page ID of this page, multiplies it by the page size, and adds the offset to obtain the physical address. This approach allows different programs to use non-overlapping segments of pages. executable->ReadAt (&(kernel->machine->mainMemory[pageTable[noffH.initData.virtualAddr/PageSize].physicalPage * PageSize + (noffH.code.virtualAddr%PageSize)]), noffH.initData.size, noffH.initData.inFileAddr); Testing Result [os24team59@localhost test]\$../build.linux/nachos -e consoleI0_test1 -e console IO test2 consoleIO test1 consoleIO test2 1return value:0 18 return value:0 [os24team59@localhost test]\$../build.linux/nachos -e consoleI0 test1 -e console

IO test3

Aborted

consoleI0_test1
consoleI0 test3

9Unexpected user mode exception 8

[os24team59@localhost test]\$

Assertion failed: line 198 file ../userprog/exception.cc