Unit 3: Concurrency

3.4. Windows APIs for Synchronization and Inter-Process Communication

Roadmap for Section 3.4.

- Windows API constructs for synchronization and interprocess communication
- Synchronization
  - Critical sections
  - Mutexes
  - Semaphores
  - Event objects
- Synchronization through interprocess communication
  - Anonymous pipes
  - Named pipes
  - Mailslots

Critical Sections

```
VOID InitializeCriticalSection( LPCRITICAL_SECTION sec );
VOID DeleteCriticalSection( LPCRITICAL_SECTION sec );

VOID EnterCriticalSection( LPCRITICAL_SECTION sec );
VOID LeaveCriticalSection( LPCRITICAL_SECTION sec );
BOOL TryEnterCriticalSection ( LPCRITICAL_SECTION sec );
```

Only usable from within the same process

- Critical sections are initialized and deleted but do not have handles
- Only one thread at a time can be in a critical section
- A thread can enter a critical section multiple times - however, the number of Enter- and Leave- operations must match
- Leaving a critical section before entering it may cause deadlocks
- No way to test whether another thread is in a critical section

Critical Section Example

```
/* counter is global, shared by all threads */
volatile int counter = 0;
CRITICAL_SECTION crit;
InitializeCriticalSection ( &crit );

/* … main loop in any of the threads */
while (!done) {
        EnterCriticalSection ( &crit );
        _try {
             counter += local_value; // any computation can be here
        }
        _finally { LeaveCriticalSection ( &crit ); }
}
DeleteCriticalSection( &crit );
```

Synchronizing Threads with Kernel Objects

```
DWORD WaitForSingleObject( HANDLE hObject, DWORD dwTimeout );

DWORD WaitForMultipleObjects( DWORD cObjects,
                              LPHANDLE lpHandles, BOOL bWaitAll,
                              DWORD dwTimeout );
```

The following kernel objects can be used to synchronize threads:

- Processes
- Threads
- Files
- Console input
- File change notifications
- Mutexes
- Events (auto-reset + manual-reset)
- Waitable timers

Wait Functions - Details

- WaitForSingleObject():
  - hObject specifies kernel object
  - dwTimeout specifies wait time in milliseconds
    - dwTimeout == 0 - no wait, check whether object is signaled
    - dwTimeout == INFINITE - wait forever
- WaitForMultipleObjects():
  - cObjects <= MAXIMUM_WAIT_OBJECTS (64)
  - lpHandles - pointer to array identifying these objects
  - bWaitAll - whether to wait for first signaled object or all objects
    - Function returns index of first signaled object
- Side effects:
  - Mutexes, auto-reset events and waitable timers will be reset to non-signaled state after completing wait functions

Mutexes

```
HANDLE CreateMutex( LPSECURITY_ATTRIBUTE lpsa,
            BOOL fInitialOwner, LPTSTR lpszMutexName );

HANDLE OpenMutex( LPSECURITY_ATTRIBUTE lpsa,
            BOOL fInitialOwner, LPTSTR lpszMutexName );

BOOL ReleaseMutex( HANDLE hMutex );
```

Mutexes work across processes

- First thread has to call CreateMutex()
- When sharing a mutex, second thread (process) calls CreateMutex() or OpenMutex()
- fInitialOwner == TRUE gives creator immediate ownership
- Threads acquire mutex ownership using WaitForSingleObject() or WaitForMultipleObjects()
- ReleaseMutex() gives up ownership
- CloseHandle() will free mutex object

Mutex Example

```
/* counter is global, shared by all threads */
volatile int done, counter = 0;
HANDLE mutex = CreateMutex( NULL, FALSE, NULL );

/*  main loop in any of the threads, ret is local */
DWORD ret;
while (!done) {
   ret = WaitForSingleObject( mutex, INFINITE );
   if (ret == WAIT_OBJECT_0)
   counter += local_value;
   else        /* mutex was abandoned */
   break;      /* exit the loop */
   ReleaseMutex( mutex );
}
CloseHandle( mutex );
```

Comparison - POSIX mutexes

- POSIX pthreads specification supports mutexes
  - Synchronization among threads in same process
- Five basic functions:
  - pthread_mutex_init()
  - pthread_mutex_destroy()
  - pthread_mutex_lock()
  - pthread_mutex_unlock()
  - pthread_mutex_trylock()
- Comparison:
  - pthread_mutex_lock() will block - equivalent to WaitForSingleObject(hMutex);
  - pthread_mutex_trylock() is nonblocking (polling) - equivalent to WaitForSingleObject() with timeout == 0

Semaphores

```
HANDLE CreateSemaphore( LPSECURITY_ATTRIBUTE lpsa,
            LONG cSemInit, LONG cSemMax,
            LPTSTR lpszSemName );

HANDLE OpenSemaphore( LPSECURITY_ATTRIBUTE lpsa,
            LONG cSemInit, LONG cSemMax,
            LPTSTR lpszSemName );


HANDLE ReleaseSemaphore( HANDLE hSemaphore,
            LONG cReleaseCount, LPLONG lpPreviousCount );
```

- Semaphore objects are used for resource counting
  - A semaphore is signaled when count > 0
- Threads/processes use wait functions
  - Each wait function decreases semaphore count by 1
  - ReleaseSemaphore() may increment count by any value
  - ReleaseSemaphore() returns old semaphore count

Events

```
HANDLE CreateEvent( LPSECURITY_ATTRIBUTE lpsa,
            BOOL fManualReset, BOOL fInitialState
            LPTSTR lpszEventName );

BOOL SetEvent( HANDLE hEvent );
BOOL ResetEvent( HANDLE hEvent );
BOOL PulseEvent( HANDLE hEvent );
```

- Multiple threads can be released when a single event is signaled (barrier synchronization)
    - Manual-reset event can signal several thread simultaneously; must be reset manually
    - PulseEvent() will release all threads waiting on a manual-reset event and automatically reset the event
    - Auto-reset event signals a single thread; event is reset automatically

    - fInitialState == TRUE - create event in signaled state

Comparison - POSIX condition variables

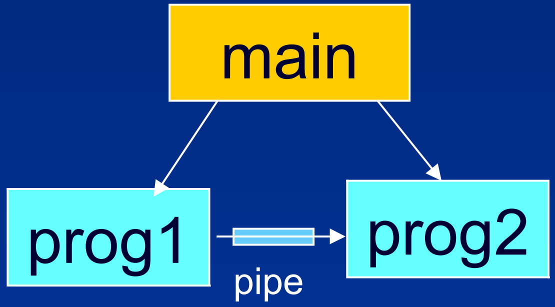
- pthread’s condition variables are comparable to events
  - pthread_cond_init()
  - pthread_cond_destroy()
- Wait functions:
  - pthread_cond_wait()
  - pthread_cond_timedwait()
- Signaling:
  - pthread_cond_signal() - one thread
  - pthread_cond_broadcast() - all waiting threads
- No exact equivalent to manual-reset events

Anonymous pipes

```
BOOL CreatePipe( PHANDLE phRead,
                 PHANDLE phWrite,
                 LPSECURITY_ATTRIBUTES lpsa,
                 DWORD cbPipe )
```

Half-duplex character-based IPC

- cbPipe: pipe byte size; zero == default
- Read on pipe handle will block if pipe is empty
- Write operation to a full pipe will block
- Anonymous pipes are oneway



I/O Redirection using an Anonymous Pipe

```
/* Create default size anonymous pipe, handles are inheritable. */
if (!CreatePipe (&hReadPipe, &hWritePipe, &PipeSA, 0)) {
     fprintf(stderr, “Anonymous pipe create failed\n”); exit(1);
}
/* Set output handle to pipe handle, create first process. */
StartInfoCh1.hStdInput  = GetStdHandle (STD_INPUT_HANDLE);
StartInfoCh1.hStdError  = GetStdHandle (STD_ERROR_HANDLE);
StartInfoCh1.hStdOutput = hWritePipe;
StartInfoCh1.dwFlags = STARTF_USESTDHANDLES;

if (!CreateProcess (NULL, (LPTSTR)Command1, NULL, NULL, TRUE,
              0, NULL, NULL, &StartInfoCh1, &ProcInfo1)) {
     fprintf(stderr, “CreateProc1 failed\n”); exit(2);
}
CloseHandle (hWritePipe);
```

Pipe example (contd.)

```
/* Repeat (symmetrically) for the second process. */
StartInfoCh2.hStdInput  = hReadPipe;
StartInfoCh2.hStdError  = GetStdHandle (STD_ERROR_HANDLE);
StartInfoCh2.hStdOutput = GetStdHandle (STD_OUTPUT_HANDLE);
StartInfoCh2.dwFlags = STARTF_USESTDHANDLES;

if (!CreateProcess (NULL, (LPTSTR)Command2, NULL, NULL, TRUE,/* Inherit handles */
            0, NULL, NULL, &StartInfoCh2, &ProcInfo2)) {
fprintf(stderr, “CreateProc2 failed\n”); exit(3);
}
CloseHandle (hReadPipe);

/* Wait for both processes to complete. */
WaitForSingleObject (ProcInfo1.hProcess, INFINITE);
CloseHandle (ProcInfo1.hThread); CloseHandle (ProcInfo1.hProcess);
WaitForSingleObject (ProcInfo2.hProcess, INFINITE);
CloseHandle (ProcInfo2.hThread); CloseHandle (ProcInfo2.hProcess);
return 0;
```

Named Pipes

- Message oriented:
  - Reading process can read varying-length messages precisely as sent by the writing process
- Bi-directional
  - Two processes can exchange messages over the same pipe
- Multiple, independent instances of a named pipe:
  - Several clients can communicate with a single server using the same instance
  - Server can respond to client using the same instance
- Pipe can be accessed over the network
  - location transparency
- Convenience and connection functions

Using Named Pipes

```
HANDLE CreateNamedPipe (LPCTSTR lpszPipeName,
            DWORD fdwOpenMode, DWORD fdwPipeMode
            DWORD nMaxInstances, DWORD cbOutBuf,
            DWORD cbInBuf, DWORD dwTimeOut,
            LPSECURITY_ATTRIBUTES lpsa );
```

- lpszPipeName: \\.\pipe\[path]pipename
  - Not possible to create a pipe on remote machine (\\. = local machine)
- fdwOpenMode:
  - PIPE_ACCESS_DUPLEX, PIPE_ACCESS_INBOUND, PIPE_ACCESS_OUTBOUND
- fdwPipeMode:
  - PIPE_TYPE_BYTE or PIPE_TYPE_MESSAGE
  - PIPE_READMODE_BYTE or PIPE_READMODE_MESSAGE
  - PIPE_WAIT or PIPE_NOWAIT (will ReadFile block?)

Use same flag settings for all instances of a named pipe

Named Pipes (contd.)

- nMaxInstances:
  - Number of instances,
  - PIPE_UNLIMITED_INSTANCES: OS choice based on resources
- dwTimeOut
  - Default time-out period (in milliseconds) for WaitNamedPipe()
- First CreateNamedPipe creates named pipe
  - Closing handle to last instance deletes named pipe

- Polling a pipe:
  - Nondestructive – is there a message waiting for ReadFile

```
BOOL PeekNamedPipe (HANDLE hPipe,
            LPVOID lpvBuffer, DWORD cbBuffer,
            LPDWORD lpcbRead, LPDWORD lpcbAvail,
            LPDWORD lpcbMessage);
```

Named Pipe Client Connections

- CreateFile with named pipe name:
  - \\.\pipe\[path]pipename
  - \\servername\pipe\[path]pipename
  - First method gives better performance (local server)
- Status Functions:
  - GetNamedPipeHandleState
  - SetNamedPipeHandleState
  - GetNamedPipeInfo

Convenience Functions

- WriteFile / ReadFile sequence:

```
BOOL TransactNamedPipe( HANDLE hNamedPipe,
            LPVOID lpvWriteBuf, DWORD cbWriteBuf,
            LPVOID lpvReadBuf, DWORD cbReadBuf,
            LPDWORD lpcbRead, LPOVERLAPPED lpa);
```

- CreateFile / WriteFile / ReadFile / CloseHandle:
  - dwTimeOut: NMPWAIT_NOWAIT, NMPWAIT_WAIT_FOREVER, NMPWAIT_USE_DEFAULT_WAIT

```
BOOL CallNamedPipe( LPCTSTR lpszPipeName,
            LPVOID lpvWriteBuf, DWORD cbWriteBuf,
            LPVOID lpvReadBuf, DWORD cbReadBuf,
            LPDWORD lpcbRead, DWORD dwTimeOut);
```

Server: eliminate the polling loop

```
BOOL ConnectNamedPipe (HANDLE hNamedPipe,
          LPOVERLAPPED lpo );
```

- lpo == NULL:
  - Call will return as soon as there is a client connection
  - Returns false if client connected between CreateNamed Pipe call and ConnectNamedPipe()
- Use DisconnectNamedPipe to free the handle for connection from another client
- WaitNamedPipe():
  - Client may wait for server‘s ConnectNamedPipe()
- Security rights for named pipes:
  - GENERIC_READ, GENERIC_WRITE, SYNCHRONIZE

Comparison with UNIX

- UNIX FIFOs are similar to a named pipe
    - FIFOs are half-duplex
    - FIFOs are limited to a single machine
    - FIFOs are still byte-oriented, so its easiest to use fixed-size records in client/server applications
    - Individual read/writes are atomic
- A server using FIFOs must use a separate FIFO for each client‘s response, although all clients can send requests via a single, well known FIFO
- Mkfifo() is the UNIX counterpart to CreateNamedPipe()
- Use sockets for networked client/server scenarios

Client Example using Named Pipe

```
WaitNamedPipe (ServerPipeName, NMPWAIT_WAIT_FOREVER);
hNamedPipe = CreateFile (ServerPipeName, GENERIC_READ | GENERIC_WRITE,
     0, NULL, OPEN_EXISTING, FILE_ATTRIBUTE_NORMAL, NULL);
if (hNamedPipe == INVALID_HANDLE_VALUE) {
     fprintf(stderr, Failure to locate server.\n"); exit(3);
}

/* Write the request. */
WriteFile (hNamedPipe, &Request, MAX_RQRS_LEN, &nWrite, NULL);

/* Read each response and send it to std out. */
while (ReadFile (hNamedPipe, Response.Record, MAX_RQRS_LEN, &nRead, NULL))
     printf ("%s", Response.Record);

CloseHandle (hNamedPipe);
return 0;
```

Server Example Using a Named Pipe

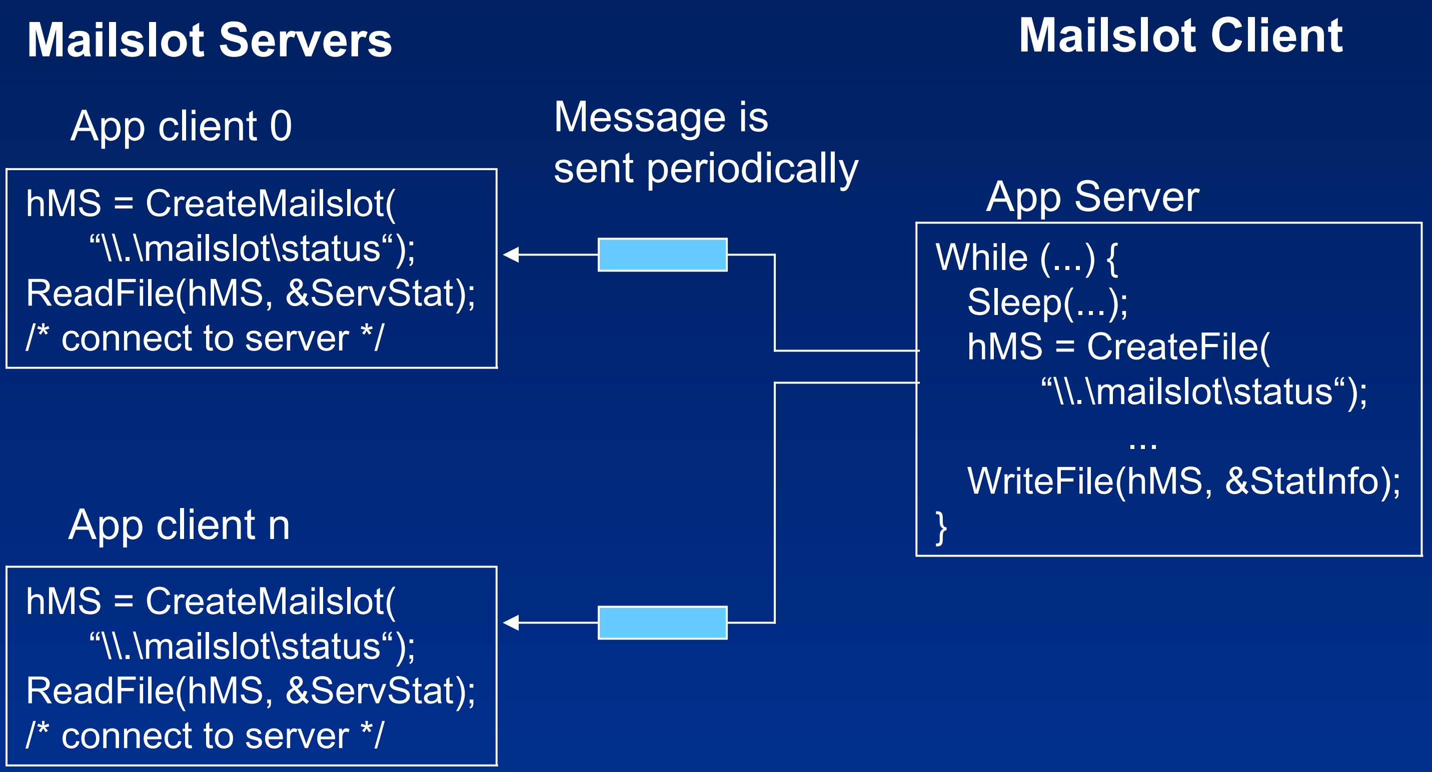
```
hNamedPipe = CreateNamedPipe (SERVER_PIPE, PIPE_ACCESS_DUPLEX,
        PIPE_READMODE_MESSAGE | PIPE_TYPE_MESSAGE | PIPE_WAIT,
        1, 0, 0, CS_TIMEOUT, pNPSA);
while (!Done) {
   printf ("Server is awaiting next request.\n");
   if (!ConnectNamedPipe (hNamedPipe, NULL)
                 || !ReadFile (hNamedPipe, &Request, RQ_SIZE, &nXfer, NULL)) {
        fprintf(stderr, “Connect or Read Named Pipe error\n”); exit(4);
   }
   printf( “Request is: %s\n", Request.Record);

   /* Send the file, one line at a time, to the client. */
   fp = fopen (File, "r");
   while ((fgets (Response.Record, MAX_RQRS_LEN, fp) != NULL))
                 WriteFile (hNamedPipe, &Response.Record,
                          (strlen(Response.Record) + 1) * TSIZE, &nXfer, NULL);
   fclose (fp);
   DisconnectNamedPipe (hNamedPipe);
}  /* End of server operation. */
```

Windows IPC - Mailslots

Mailslots bear some nasty implementation details; they are almost never used

- Broadcast mechanism:
  - One-directional
  - Mutliple writers/multiple readers (frequently: one-to-many comm.)
  - Message delivery is unreliable
  - Can be located over a network domain
  - Message lengths are limited (Win2k: < 426 byte)
- Operations on the mailslot:
  - Each reader (server) creates mailslot with CreateMailslot()
  - Write-only client opens mailslot with CreateFile() and uses WriteFile() – open will fail if there are no waiting readers
  - Client‘s message can be read by all servers (readers)
- Client lookup: \\*\mailslot\mailslotname
  - Client will connect to every server in network domain

Locate a server via mailslot



Mailslot Servers

App client 0

```
hMS = CreateMailslot(
      “\\.\mailslot\status“);
ReadFile(hMS, &ServStat);
/* connect to server */
```

App client n

```
hMS = CreateMailslot(
      “\\.\mailslot\status“);
ReadFile(hMS, &ServStat);
/* connect to server */
```

Message is sent periodically

Mailslot Client

App Server

```
While (...) {
   Sleep(...);
   hMS = CreateFile(
          “\\.\mailslot\status“);
                ...
   WriteFile(hMS, &StatInfo);
}
```

Creating a mailslot

```
HANDLE CreateMailslot(LPCTSTR lpszName,
           DWORD cbMaxMsg,
           DWORD dwReadTimeout,
           LPSECURITY_ATTRIBUTES lpsa);
```

- lpszName points to a name of the form
  - \\.\mailslot\[path]name
  - Name must be unique; mailslot is created locally
- cbMaxMsg is message size in byte
- dwReadTimeout
  - Read operation will wait for so many milliseconds
  - 0 – immediate return
  - MAILSLOT_WAIT_FOREVER – infinite wait

Opening a mailslot

- CreateFile with the following names:
  - \\.\mailslot\[path]name - retrieve handle for local mailslot
  - \\host\mailslot\[path]name - retrieve handle for mailslot on specified host
  - \\domain\mailslot\[path]name - returns handle representing all mailslots on machines in the domain
  - *\mailslot\[path]name - returns handle representing mailslots on machines in the system‘s primary domain: max message length: 400 bytes
  - Client must specifiy FILE_SHARE_READ flag
- GetMailslotInfo() and SetMailslotInfo() are similar to their named pipe counterparts

Further Reading

- Mark E. Russinovich, David A. Solomon and Alex Ionescu, "*Windows Internals*", 6th Edition, Microsoft Press, 2012.
  - Chapter 3 - System Mechanisms
  - Synchronization (from pp.176)
  - Named Pipes and Mailslots (from pp. 612)

  Remark: this chapter will be in part 2 of 7th edition!
- Jeffrey Richter, Programming Applications for Microsoft Windows, 4th Edition, Microsoft Press, September 1999.
  - Chapter 10 - Thread Synchronization
  - Critical Sections, Mutexes, Semaphores, Events (from pp. 315)
- Johnson M. Hart, Win32 System Programming: A Windows® 2000 Application Developer's Guide, 2nd Edition, Addison-Wesley, 2000.