Signals

Within the UNIX virtual computer (process) model, signals serve a role analogous to interrupts in a physical computer. They (can) the cause execution of the user-mode program to be interrupted and transfer to a pre-established handler, just like vectored hardware interrupts. They can also be masked and unmasked.

Signals may be viewed as taking place in two stages: **sending** (aka **generating** or **posting**) a signal, and then **delivery**, i.e. the action in the recipient process which results. Signals may be sent explicitly by one user process to one or more processes (including itself) via the `kill` system call. The kernel may also send different signals to a process as a result of errors or events, in which case, like hardware interrupts, signals can be said to be **synchronous** or **asynchronous**, if, respectively, the cause of the signal can or can not be associated with a particular instruction or operation that the process is currently executing. Here are some common sync and async signals:

- Illegal memory access: SIGSEGV or SIGBUS (sync)
- Illegal instruction opcode: SIGILL (sync)
- Hangup on controlling terminal session: SIGHUP (async)
- Keyboard interrupt (typically ^C key) from controlling terminal: SIGINT (async)
- Asynchronous I/O notification: SIGIO (async)
- Death of a child: SIGCHLD (async)

kill system call

A process can send any other process, including itself, any signal by using the `kill` system call:

```
int kill(pid_t pid,int sig)
```

The user id of the killer must match the recipient, i.e. you can't willy-nilly kill other folks' processes. However, the super-user (uid==0) may send any process a signal. Special values can be used for `pid` to do nifty things:

- pid== -1: Kill all processes with user id equal to killer.
- pid== -n: (n!=1) Kill all processes in process group n.
- pid==0: Send to all processes in the process group

The name "kill" is a bit of a misnomer. Depending on a number of things that we will discuss momentarily, sending a signal to a process will not necessarily cause it to die. ["process groups" are beyond the scope of this course]

The `sig` number is best specified using a constant from the system header files, as discussed below. A 0 value for `sig` doesn't actually send the signal, but checks whether it would have been possible to do so. It can be used to probe the existence of a process.

Pre-defined UNIX signal numbers and behaviors

UNIX defines dozens of signals, some system-dependent, which represent different conditions. Symbolic names, such as `SIGHUP`, are found by #includ'ing `<sys/signal.h>`. The assignment of signal numbers is kernel-specific. Although certain signal numbers such as 1, 2, 3, 9 and 15 are unlikely ever to change, good programmatic practice is to use the symbolic names at all times. The following signal definitions are correct for most Linux kernels running on the x86 architecture:

```
Sig#      Name              Def Act           Desc
1         SIGHUP            Terminate Hangup on controlling tty
2         SIGINT            Terminate Keyboard interrupt
3         SIGQUIT           Coredump  Keyboard abort
4         SIGILL            Coredump  Illegal Instruction
5         SIGTRAP           Coredump  Tracing/breakpoint trap
6         SIGABRT           Coredump  Abort (raised by abort(3))
7         SIGBUS            Coredump  Bus Error (bad memory access)
8         SIGFPE            Coredump  Floating Point/Math Exception
9         SIGKILL           Terminate Non-blockable kill
10        SIGUSR1           Terminate User definable
11        SIGSEGV           Coredump  Segmentation Violation (non-exist addr)
12        SIGUSR2           Terminate User definable
13        SIGPIPE           Terminate Write to a broken pipe
14        SIGALRM           Terminate Alarm clock (see alarm(2))
15        SIGTERM           Terminate Normal terminate request
16        SIGSTKFLT         Terminate Co-processor stack fault (UNUSED)
17        SIGCHLD           Ignore    Child exit/status change
18        SIGCONT           Resume    Continue stopped process
19        SIGSTOP           Stop      Stop process (unblockable)
20        SIGTSTP           Stop      Keyboard stop
21        SIGTTIN           Stop      Stopped waiting for tty input
22        SIGTTOU           Stop      Stopped waiting for tty output
23        SIGURG            Ignore    Urgent data on socket
24        SIGXCPU           Coredump  Exceeded CPU time limit
25        SIGXFSZ           Coredump  Exceeded file size limit
26        SIGVTALRM         Terminate Virtual alarm clock (see setitimer(2))
27        SIGPROF           Terminate Profiling timer
28        SIGWINCH          Ignore    Tty window size change
29        SIGIO             Terminate Signal-driven I/O (aka SIGPOLL)
30        SIGPWR            Ignore    Power going down
31        SIGSYS            Coredump  Bad system call #
```

To learn more about signals on your Linux platform, `man 7 signal`

Pending signals and signal masks

The kernel maintains two bitfields concerning signals for each process. Conceptually, these are arrays of boolean (1-bit) values. There is an element of this array for each valid signal number (signal 0 is never a valid signal, so this array conceptually starts at index

1). A bit in the *pending signals* array is set when a particular signal is posted to that process. Note that since this is a boolean array, not an integer array, the kernel does not "count" *how many* pending signals there are of a given signal number, just the presence or absence of such.

The other such (conceptual) array represents the *signal mask*, or the list of signal numbers which are currently blocked. A 1 bit means that signal is blocked (masked) while 0 means it can go through. When a signal is posted to a process and that signal is currently masked, the signal is not forgotten, because the corresponding bit in the pending signals array is set first. The pending signal can not be delivered when it is blocked, but if and when that the signal number is un-blocked, that signal will be delivered. We will discuss the mechanisms for changing the signal mask shortly.

When is the signal delivered?

Referring to the process state diagram shown in the previous Unit #3, *delivery* of a signal only happens when the process is in the KERNEL RUNNING state and is about to transition back to USER RUNNING. At this point, we see the note "Check for signals." If there are any bits set in the process' pending signals bitmap which are not being blocked, then the pending signal is acted upon. That is the moment of delivery (we'll see later what happens if multiple signals are pending). After delivery, the pending bit is cleared.

When a signal is generated in another process, that process is obviously in the KERNEL RUNNING state (since it is executing the `kill` system call). However, the target process is not necessarily in a RUNNING (user or kernel) state. Therefore, delivery of the signal does not necessarily happen right after generation. It is indeterminate when this happens.

On a uniprocessor system, the generating process is on the lone CPU and the target process must therefore be in a non-RUNNING state (unless a process is sending a signal to itself). Therefore delivery can not take place until the scheduler decides that it is the target process's turn to be scheduled-in.

However, on a multi-CPU system, the target process might be in a RUNNING state on a different CPU than the sender. Rather than wait for potentially a full clock tick cycle for the kernel to regain control of the target process and deliver the signal, under these circumstances the kernel, running on behalf of the sender process on say CPU #1, causes a hardware **inter-processor interrupt (IPI)** to be sent to the target, say on CPU #2. This forces CPU #2 to run the interrupt handler, which gives control back to the kernel.

When the signal is being generated by the kernel in response to a fault (e.g. bad memory access), that is a case of the process sending a signal to itself. The kernel posts the appropriate signal (e.g. SIGSEGV) to the currently running process, and the signal is

delivered almost immediately, as soon as control tries to return to USER RUNNING.

Blocked signals are not delivered at all while the signal is still blocked, and then are delivered at some indeterminate time after the signal becomes unblocked.

Signals and Sleeping

When a process is in the SLEEPING-INTERRUPTIBLE state mentioned in Unit #3, the arrival of a signal, which is not currently being blocked, will cause the target process to wake up from the sleep. It will transition to the READY state and then, when it is scheduled, to KERNEL RUNNING and then try to return to USER RUNNING, at which point the kernel acting on behalf of the process will deliver the signal. However, if the target process is in SLEEPING-UNINTERRUPTIBLE, then the arrival of a signal does not have an immediate effect. The signal is remembered but the target continues to sleep. This means that there is no user-level way to wake up a process in an uninterruptible sleep, except when the event for which it is waiting is satisfied.

As we'll see in Unit #8, the decision of whether a sleep event is interruptible by a signal is made on a case-by-base basis in the kernel code. Generally, things that are expected to be "long" waits, such as waiting for keyboard or network I/O, are interruptible while "short" waits such as waiting for disk I/O are un-interruptible. Unfortunately the Linux documentation is extremely poor at describing this and often one has to read the kernel source code to figure out the correct answer.

Signal delivery & dispositions

Upon signal delivery, the pending signal bit for that signal number is cleared. There are several basic outcomes or "dispositions". As we will see shortly, the process can establish the desired outcomes on a per-signal-number basis. The possible dispositions are: terminate, terminate w/ core dump, stop, resume, ignore, handle. Let's look at each one in detail:

Process Termination by delivery of signal

If the disposition of a particular signal is "terminate" and that signal is delivered, the receiving process immediately exits, because the kernel effectively makes the `_exit` system call on behalf of the process. This means that, just as if `_exit` had been called voluntarily by the program:

- All open file descriptors are closed
- All memory in use by the process is released
- The reference count to the current directory of the process is decremented
- Other resources that we haven't covered, such as locks, are released
- An `rusage` structure is left behind along with the exit status, to be picked up by a

parent process using the `wait` family of system calls.

Note that stdio buffers are *not* flushed here, because the code to flush them doesn't run -- the process instantly exits. This is why debugging output is usually sent to `stderr`, the pre-defined `FILE *` stdio stream which has buffering set to unbuffered.

Termination by signal and termination by `_exit` system call are mutually exclusive, and they are the only two ways that a process can die. We saw in the last unit that these two mutually exclusive causes of death are encoded in the 16-bit exit status word that the `wait` system call retrieves.

Termination with core dump

In some cases determined by signal number (see table above), termination is accompanied by the generation of a **coredump** file. This file is named `core` and is created in the current working directory of the process, as if the process itself had opened this file for creation/writing and wrote to it. If the process does not have permission to create this file, it is not created. A resource limit (see the `ulimit` command or the `setrlimit` system call) can be set to limit the maximum size of the core file. Be careful: many popular Linux "distros" set the default core ulimit to 0, which means core files are not generated. The core dump file contains the contents of all relevant memory sections ("core" is an old term for main memory) at the time of termination, as well as the registers. This allows a debugger (such as gdb or adb) to reconstruct the call stack and the contents of all local and global variables, and determine where in the code the offense occurred. The format of the core dump file is architecture-specific.

Ignore the signal

When a signal is posted to a process which is IGNoring that signal, *and* that signal is not currently blocked, then the signal will be discarded. However, if it is masked it is remembered in the pending signals array (because the disposition could be changed later and then the signal un-blocked). Certain signals (SIGKILL and SIGSTOP) can't be ignored.

Stop and Resume

This is used in conjunction with **job control**, which allows a running process or processes, attached to a user's terminal session, to be frozen, unfrozen, detached or re-attached to that terminal. Stopping the process is not the same as terminating it. Stop is the default action for certain signal numbers (see table above) which the kernel has assigned for job control. **Resume** is the default action for `SIGCONT`, which is the only signal which can produce this action.

Handle the Signal

If the disposition has been set to a valid function address using the `signal` or `sigaction` system calls documented below, then the signal handler is invoked (see below).

Establishing signal disposition

Classically, the `signal` system call provides the means for controlling signal disposition, although it can not block or unblock signals.

```
void (*signal(int signum, void (*handler)(int)))(int);
```

This rather complicated prototype indicates that, for the signal `signum`, the handler will be set to the function `handler` (which takes an `int` argument). `signal` will return the previous value of the handler, which can be stashed away if it is desired to restore it later. On failure, `signal` returns the value `SIG_ERR`.

In addition to a bona-fide signal handler function address, `handler` can be:
• SIG_IGN: Ignore the signal or
• SIG_DFL: Reset to the default handling for this signal, as given in the table above. Note that certain signals have a default disposition which is to Ignore (SIGCHLD, SIGURG, SIGWINCH, SIGPWR).

These are numbers chosen so that they can't possibly be the valid address of a function.

The signal handler

A signal handler is an ordinary function. When a signal is delivered and the disposition of that signal number is to invoke a handler, it appears as if the handler function had been called from the instruction within the program that was executing when the signal was delivered. This is analogous to an interrupt service routine in responding to a hardware interrupt.

The signal handler function is called with a single integer parameter, the signal number that is being handled (using the `sigaction` interface, additional parameters can be passed. This is beyond the scope of this unit). The same handler function can be specified for multiple signals and this parameter can be used to disambiguate.

In most versions of UNIX, including Linux, the default behavior is that when signal *n* is delivered to a process and handled, *n* is temporarily added to the blocked signals mask upon entry to the handler, at the same time that the pending signal bit for *n* is cleared. This prevents the signal handler from being called re-entrantly. (If you don't want this behavior, see discussion of the `SA_NODEFER` flag). Upon return from the handler, the original blocked signal mask is restored. If the signal *n* was received while the handler's

was executing, then the handler will be immediately re-invoked (but this is not re-entrant).

The signal handler function has a return type of void. When the signal handler function returns, execution resumes at the point of interruption. For synchronous signals, execution resumes by re-trying the instruction that caused the fault. If the cause of the fault has not been corrected, then the program can get stuck in an endless loop of fault, handler, fault, handler, etc.

If the signal handler does not return, it either exits the program, or takes a "long jump" :

setjmp/longjmp

Consider a command-line mathematical program. The main loop executes commands through a function `do_command`. Eventually, one of these commands leads, via a long chain of function calls, to:

```
long_compute()
{
        /* a very long calculation */
}
```

At some point during `long_compute()`, the user gets impatient and hits ^C. We wouldn't want to abort the entire program and potentially lose unsaved data. We'd like to return to the command prompt. We would also like to avoid cluttering the code with frequent checks of some sort of global "abort" flag. Thankfully, C has a user-level mechanism known as "setjmp/longjmp". Another name for this is **non-local goto**.

```
#include <setjmp.h>

jmp_buf int_jb;             /*typedef'd in setjmp.h, really a int[] */

void int_handler(int sn)
{
        longjmp(int_jb,1); /* No need for & since it is an array */
        /* NOTE: there is a flaw in this code */
        /* See text for discussion of siglongjmp and other solutions */
}

main()
{
 char cmdbuf[BUFSIZ];
        (void)signal(SIGINT,int_handler);
        for(;;)
        {
                printf("Command> ");
                if (!fgets(cmdbuf,sizeof cmdbuf,stdin)) break;
                if (setjmp(int_jb)!=0)
                {
                        printf("\nInterrupted\n");
```

```
                        continue;
                }
                do_command(cmdbuf);
        }
}
```

`setjmp`, from the program's standpoint, appears to be a function that is called once, and returns one or more times. `setjmp` stores context information, such as the program counter, stack pointer and register contents, into the `jmp_buf`, which is simply a `typedef` for an array of a sufficient size to hold this information. The program counter location stored is the address of the instruction following the call to setjmp. setjmp returns 0 when it is called (for the first time.)

A call to `longjmp` uses the context information stored in the supplied `jmp_buf` to return control to the setjmp point. The second argument will be the perceived return value from setjmp. It can not be 0, and if 0 is supplied the argument will silently be changed to 1. `longjmp` restores all of the saved register values, except the one used to indicate the return value from a function, which it sets to the supplied value.

The jump buffer must be visible both to setjmp and to longjmp, which means it must be a global variable, not a local variable. Because longjmp rolls back the stack frame to its state when setjmp was called, longjmp must be called from a function descended from the one in which setjmp was called. Otherwise, the stack frame may have already been overwritten by other function calls and sheer terror and chaos will reign.

In effect, longjmp provides the ability to `goto` across function boundaries. As is the case with ordinary `goto`, the use of `setjmp/longjmp` is not (necessarily) an evil thing! Frequently it is the cleanest way to bail out of deep code.

Note that setjmp/longjmp are entirely a user-level mechanism. They are not system calls.

Signal Mask Restoration After Longjmp

When a signal handler takes a longjmp, the restoration of the blocked signals mask does not take place. In the example above, subsequent SIGINT will not have any effect, because the blocked signal mask will have SIGINT set. There are several possible solutions:

• We could use `sigaction` to establish the signal disposition and specify `SA_NODEFER` in the `sa_flags`. Then the handler will be invoked without masking SIGINT. If a second SIGINT arrives between the invocation of the handler and the longjmp, the handler will be called re-entrantly. In this particular example, no harm will come from that (the `longjmp` operation is idempotent) so that's a valid solution.

• We could use the `sigsetjmp` library function instead. This function also saves the state of the process blocked signals mask inside the context buffer (which is now of type `sigjmp_buf`). The corresponding `siglongjmp` library function restores the mask

just before completing the longjmp. *Caveat*: The restoration of the mask and the jump are not *atomic*. There is a brief *race condition* window where the signal is unmasked but the longjmp hasn't happened yet. Therefore, if another instance of SIGINT had arrived while the handler was running, the signal handler may wind up getting invoked re-entrantly. Again, in the particular example above, this does not cause a problem.

• After we have arrived back at the setjmp location from the handler, we could call `sigprocmask` to unmask SIGINT. This may result in a nearly immediate re-invocation of the handler, but this is not a re-entrant invocation, because the first instance of the handler has already jumped out.

Masking/Blocking signals

We will now explore how to manipulate the process's blocked signals mask. The block/unblock mechanism is most useful in protecting **critical regions** of code, where data structures are in an inconsistent state. For example, consider a routine to transfer a balance between accounts:

```
transfer_balance(a,b,n)
struct account *a,*b;
{
         a->balance-=n;
         b->balance+=n;
}
```

Every 24 hours, we want to prepare a summary report:

```
main()
{
         /*...*/
         signal(SIGALRM,alarm_handler);
         set_alarm();
         /*...*/
}

alarm_handler()
{
 struct account *p;
         for (p=first_account;p;p=p->next)
                  printf("Account %s   Balance %d\n",a->name,a->balance);
         set_alarm();
}

set_alarm()
{
         alarm(24*3600);
}
```

This uses the `alarm` system call to set an alarm which, at the specified number of seconds in the future, will cause delivery of SIGALRM to the process.

Consider what happens when the alarm signal arrives between the two statements of `transfer_balance`. The data structure is in an inconsistent state and the summary report is incorrect. We will examine these issues of concurrency and synchronization in greater detail in Unit 6. For now, the best fix is to block the alarm signal during the critical region:

```
transfer_balance(a,b,n)
struct account *a,*b;
{
 sigset_t set;
          sigemptyset(&set);
          sigaddset(&set,SIGALRM);
          sigprocmask(SIG_BLOCK,&set,NULL);
          a->balance-=n;
          b->balance+=n;
          sigprocmask(SIG_UNBLOCK,&set,NULL);
}
```

Each process has a bit field which represents which signals are blocked. The `sigprocmask` system call can be used to set bits in that mask, remove bits, set the entire mask at once, or query the current value of the mask. It uses a data type `sigset_t` to abstract the issue of how many bits are in that vector, and what data type has enough bits to hold it. For example, on the Linux kernel, where there are 64 signal numbers and when running on an architecture with 32 bit ints, it is defined in the system header files as:

```
typedef struct {
        unsigned long sig[_NSIG_WORDS];                  //this works out to [2]
} sigset_t;
```

If the SIGALRM signal arrives while it is blocked, it will stay in the pending signal set until the second `sigprocmask` system call removes the mask. Shortly thereafter the signal will be delivered and the handler will be invoked.

The sigaction interface

In the early years of UNIX, there were some inconsistencies in how the signal(2) system call functioned, in particular some UNIX versions reset the signal disposition of the signal in question upon entry to the handler. Because of the potential confusion, a new system call was introduced among all UNIX variants in the 1990s. The `sigaction` system call uses a more complicated interface, but can accomplish a lot more in a single call.

```
int sigaction(int sig,const struct sigaction *act, struct sigaction *oldact)

struct sigaction {

          void     (*sa_handler)(int);
          sigset_t sa_mask;
```

```
        int      sa_flags;
        /* Some more stuff...pretty complicated, read man page */
};
```

As with `signal`, `sa_handler` can be set to SIG_DFL to reset to default action, or SIG_IGN to ignore the signal, or the address of the signal handler function. `sa_flags` is a bitwise flags word that specifies a potpourri of options, including:

• SA_RESETHAND: Restore signal action to SIG_DFL when entering handler, aka unreliable signal semantics.

• SA_NODEFER: Do not automatically block signal while being handled. Aka SA_NOMASK

• SA_SIGINFO: Call the signal handler with 3 arguments. The first argument is the signal number. The second is a pointer to a `siginfo_t` structure which contains a lot of useful (and potentially architecture-specific) information about the cause of the signal. The third argument is a pointer to a `ucontext_t` structure which represents the context at the point in the program at which the signal was received. This argument is primarily for use in multi-threaded programs.

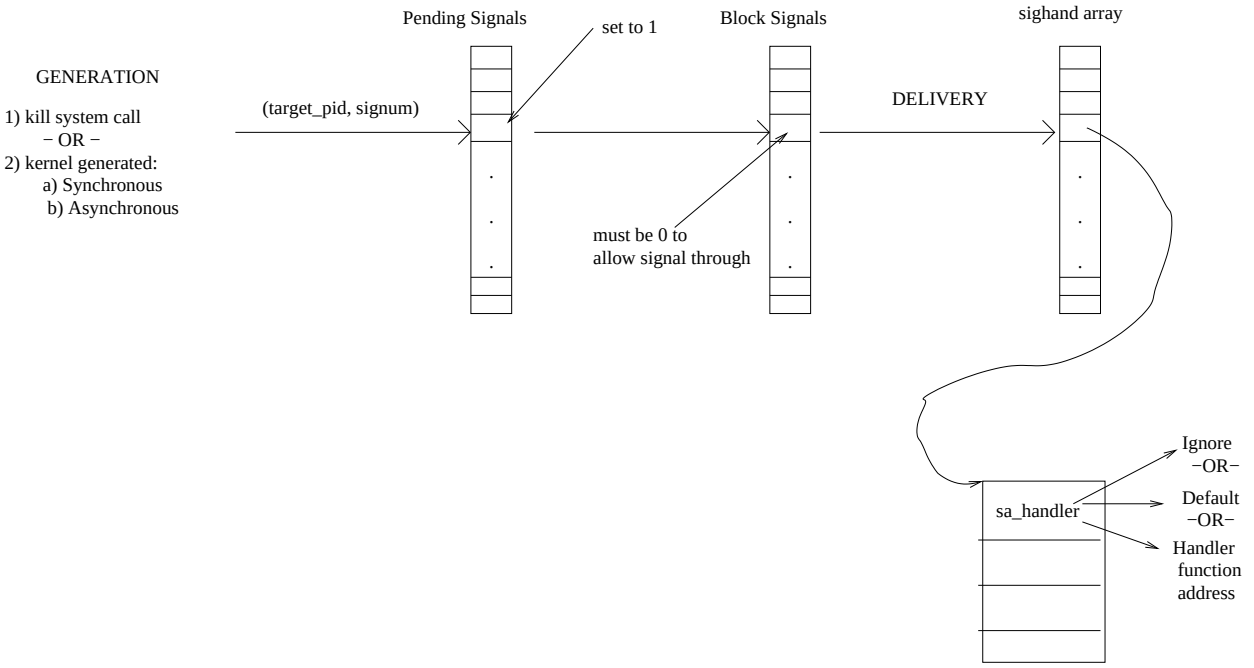
• SA_RESTART: Increases the likelihood that system calls interrupted by this signal and handled will restart when the handler returns. See discussion below under "Interrupted System Calls"

Make sure to set sa_flags=0 if you don't want any flags. Otherwise the field may contain random garbage that will be mis-interpreted as various SA_XXX flags!

`sa_mask` describes which signals to block upon entry to the handler, in addition to the signal being handled itself, which is blocked unless SA_NODEFER has been specified. Be sure to set this correctly with `sigemptyset`, `sigaddset`, etc. otherwise extraneous signals may be masked during your handler's invocation.

On modern releases of Linux, the `signal` system call is just a wrapper which translates to a `sigaction` system call, with the sa_flags set to 0 and the sa_mask set to empty. `man 2 signal` documents this in more detail.

The diagram below provides a pictorial overview of how signals work:



Real-time signals

Signals were originally conceived as a way to terminate or control processes, hence the rather severe name `kill` for the system call to send a signal. Signals have been used as a primitive inter-process communications (IPC) mechanism, e.g. a daemon process which responds to a SIGHUP and re-reads its configuration files. However, the fact that traditional signals don't queue and carry no additional data makes them of limited use for IPC. In a later unit, we will see better ways for processes to send messages to each other.

On some more modern versions of UNIX, including Linux, **real-time** signals are supported. These are numbered `SIGRTMIN` to `SIGRTMAX` and have no pre-defined meanings. Under the current Linux kernel, signals 32 through 63 are real-time signals. However signals 32-34 are used by the threads library, and should thus be avoided by other code. Therefore SIGRTMIN is defined as 35. Your mileage may vary, so always use the macros and avoid hard-coded signal numbers.

Unlike standard signals, real-time signals queue. If a process is sent, e.g. 5 instances of signal #35 while that signal is being blocked, upon un-blocking the signal, it will be delivered to the process 5 separate times. Furthermore, the real time signals are delivered in the order in which they were sent.

The `sigqueue` system call is similar to `kill`, but allows the sender of the signal to attach a small, opaque chunk of data:

```
int sigqueue(pid_t pid, int sig, union sigval value)
```

```
union sigval {
         int sival_int;
         void *sival_ptr;
}
```

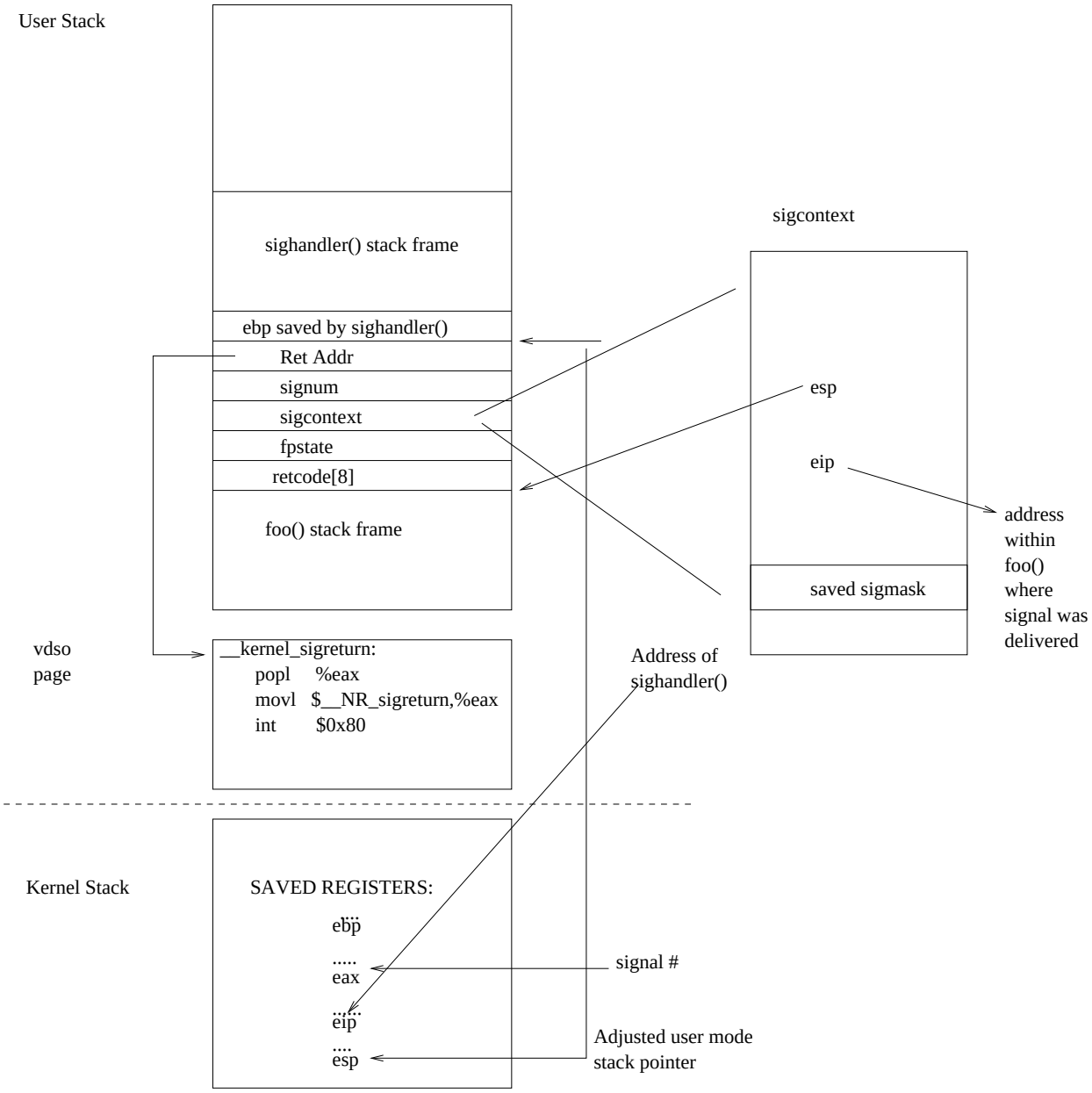
The union will be the larger of the int size or the pointer size for that machine. The contents are passed along to the signal handler by the kernel and are opaque (the kernel does not interpret the union value). `sigqueue` could also be used to send a traditional signal (signal number < 32), but such a signal still won't queue. The opaque data will be delivered, but if multiple instances of the traditional (not real-time) signal occur, newer instances will overwrite the earlier data.

Invocation of and return from signal handlers -- kernel interactions

The kernel controls the invocation of a signal handler. When a signal is delivered to a process and the disposition is set to a handler, the kernel reaches into the user-mode stack and creates a new stack frame which makes it appear that the handler was called from whatever point in the program that we happened to be in when the signal arrived.

However, there is another trick: In order to implement certain semantics, such as restoring the original blocked signals mask upon exit from the handler, the kernel needs to place a "hook" in the stack. The return code in this artificial stack frame is not the program counter location of the point where the signal was received. Instead, it is a pointer to a small region of memory that the kernel has created (once, when the program was started) and populated with a few bytes of executable code which cause the `sigreturn` system call to be invoked. This is not a system call that one would generally invoke explicitly from within program code!

When the kernel set up the stack frame, it stashed the real return address, along with a copy of all the registers, the old signal mask, and a bunch of other stuff, all inside of that stack frame. The `sigreturn` syscall looks back at the user-mode stack and fetches these saved values, restors the signal mask and performs any other needed restoration actions, then returns back to user mode, with the program counter *now* set to the point at which execution should resume in the main program, and the stack pointer accordingly restored to its correct place.



Interrupted System Calls

Certain system calls are designated as "long" calls. Generally, these are calls that may block for an indefinite period of time, for example, reading from the terminal or network connection. When an asynchronous signal arrives while the process is blocked in a "long" system call (of course a synchronous signal can not arrive at this point since the process is not executing instructions), and that signal is handled with a signal handler function, the system call is said to have been interrupted. Assuming the signal handler returns (it doesn't longjmp out or exit the process), the system call will return a failure

with errno set to EINTR (Interrupted System Call).

(To be clear, the system call returns but the handler is invoked first. I.e. if we look at the stack trace, the handler appears to have been called from the point of just returning from the system call library function. Then when the handler returns, we resume from that point and the code following system call return executes. This section about "interrupted system calls" applies only to system calls that are interrupted by a signal before completing, and the signal is handled, and the signal handler returns.)

Often, this is exactly what one wants. However, if it is necessary to make the signal handling perfectly transparent, the system call must be "restarted" when the signal handler returns and the process must go back to sleep until the system call finishes. To specify that behavior, use the SA_RESTART flag with `sigaction`. This flag defaults to OFF.

Restart means that the system call is effectively made a second time with identical parameters. This doesn't always make sense, specifically if the previous, interrupted system call had some non-idempotent effect, such as reading or writing bytes from a file descriptor. Therefore, in certain situations, the Linux kernel will not restart an interrupted system call, even though SA_RESTART is on, and will give the EINTR error, or will give a non-error return value from the system call reflecting the partial work that the system call did before being interrupted. In some cases, the kernel must go through great internal work to make a system call transparently restartable, although this is not visible to the user.

Then there are a few rare situations where the kernel will *always* restart a given interrupted system call, regardless of the SA_RESTART flag.

The moral of the story: When coding a program that uses signal handlers, most system call errors have to be checked and special logic used so that `EINTR` is not treated as a fatal error, if there is a possibility that a signal is received and handled while that system call is sleeping.

SIGCHLD

The `SIGCHLD` signal is somewhat special. By default, whenever a process terminates, a `SIGCHLD` signal is sent to its parent. The default disposition (SIG_DFL) of `SIGCHLD` is to ignore the signal, but this is not quite the same thing as explicitly ignoring the signal with `sigaction` or `signal`. The distinction has to do with compatibility with different varieties of UNIX, some of which (including Linux) maintain that when `SIGCHLD` is explicitly ignored (disposition is set to SIG_IGN), it tells the kernel that the parent has no interest in the child, and thus a zombie will not be created.

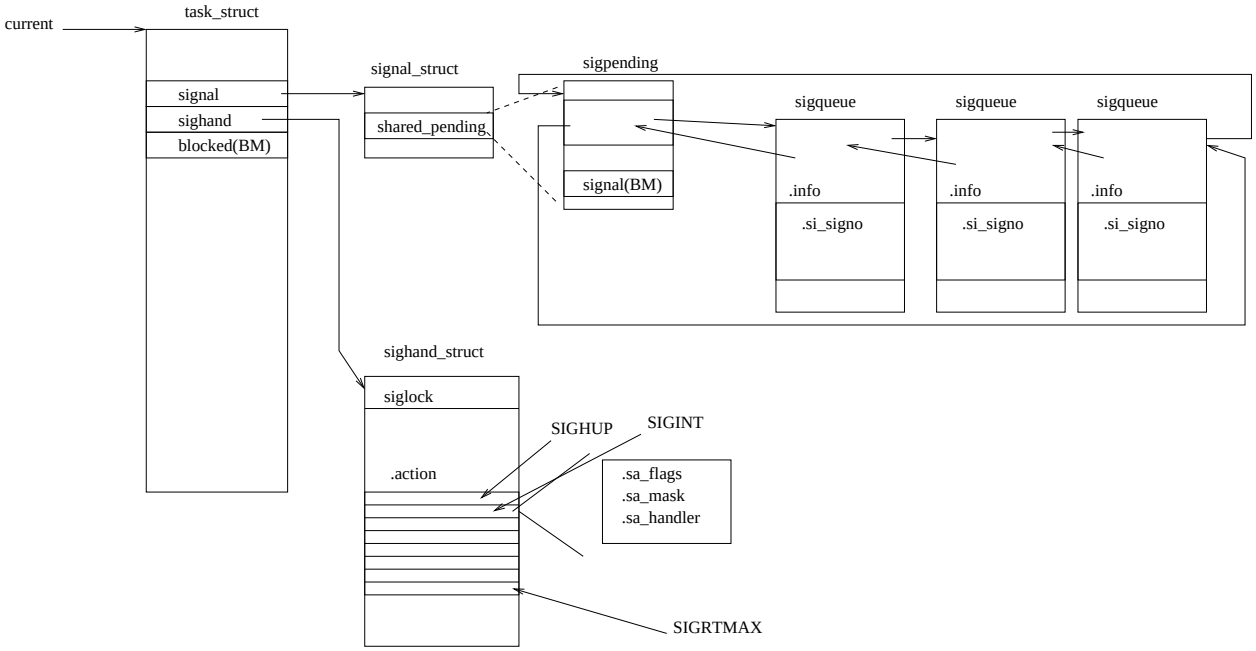
Signal interactions with fork and exec

During a successful `exec` system call:
• The kernel clears the set of pending signals. The set of blocked signals remains the same.
• Any signals which were set to go to a signal handler are changed to `SIG_IGN`, because in the new executable, the address of the signal handler(s) would obviously be invalid.
• If the SIGCHLD signal was being explicitly ignored, its disposition is reset to the default (which is to implicitly ignore it).

After a `fork`, the set of pending signals for the child process is initialized to be empty. The parent is not affected. The signal disposition in the child and set of blocked signals is exactly the same as the parent.

Visualizing kernel data structures related to signals

There are three members of the `struct task_struct` which keep track of signals on a per-process basis. They are illustrated in the figure below.



The `sighand_struct` is essentially an array of structures very similar to the `struct sigaction` used in the system call of the same name. This system call simply installs the provided `sigaction` structure into the kernel's table for the specified process and signal number, subject of course to proper permissions and error checks.

The `signal_struct` (note the awful naming conventions) keeps track of pending signals. We are glossing over the details of "shared" signals which can be delivered to any thread in a multi-threaded program and "private" signals. The `shared_pending`

member is embedded in the `signal_struct` and anchors a doubly-linked list of pending signals, each of which is represented by a `struct sigqueue`. There is also a bitmask (unfortunately named `signal`) which allows the kernel to quickly determine which signals are pending by signal number.

When a signal is posted to a process, the kernel adds it to this "queue" of pending signals. Because signals 1 through 31 do not queue or "count", if there is already a pending signal of the same number, the new signal is discarded. However, real-time signals (32 through 63) do add to the queue under all circumstances.

When the kernel checks to see if any signals need to be delivered to the process (this happens whenever returning to user mode) it examines the bitmask in signal number order, and picks the lowest-numbered pending signal. It runs through the list of pending signals and removes the one with the matching signal number, then delivers that signal. At the same time, the corresponding bit in the pending signals array is cleared if that is the last instance of that signal number in the pending signals queue. For non-real-time signals, that is always the case since the queue can not contain multiple instances of the same signal number.

During a `clone` system call, if the `CLONE_SIGHAND` flag is set, the parent and child process share the same `sighand_struct` in kernel memory. This flag is normally set when threads are created within a multi-threaded program, therefore any thread can call `sigaction` and affect the signal disposition for the entire program. Of course, during `fork`, all clone flags are 0, and the parent and child have separate signal handler tables after the fork (the child’s starting out as an exact copy of the parent’s). There are additional complications regarding signal handling in multi-threaded programs which we are not going to cover in this course.

Pipes

The UNIX **pipe** provides the fundamental means of interprocess communication, in accordance with the UNIX philosophy of providing small, flexible tools that can be combined to build up larger solutions.

A pipe is a uni-directional FIFO. It is created with the `pipe` system call:

```
main()
{
 int fds[2];
         if (pipe(fds)<0)
         {
                  perror("can't create pipe");
                  return -1;
         }
```

Two new file descriptor numbers are allocated and returned via the two-element array `fds`. `fds[0]` is the read side of the pipe, `fds[1]` is the write side.

Although a pipe is accessed like a file, using file descriptors, there is no path in the filesystem which refers to the pipe. This means that processes which communicate via a pipe must be descended from a common process which created the pipe and passed along the file descriptors via the I/O redirection methods covered in Unit 3. This is a common application when spawning a pipeline of commands from a UNIX shell, in which all of the command processes are descended from the same shell process. In subsequent units, we will explore other pipe-like mechanisms that allow arbitrary processes to communicate, including processes on different host systems.

Pipe properties

• The pipe is uni-directional. An attempt to read from the write side, or write to the read side, will be greeted with EBADF. On some systems (e.g. Solaris), the pipe is bidirectional, however, this behavior should not be relied upon.
• The pipe is a FIFO. The order of the bytes written to the write side of the pipe will be strictly preserved when read from the read side. Data will never be lost, modified, duplicated or transferred out of sequence. However, if multiple processes are attempting to read from the same pipe, the distribution of data to each will be unpredictable.
• Message boundaries are not preserved by the pipe. If one process performs, e.g., 4 small writes to the pipe, and later a read is performed, all of the data will be returned as one large chunk. In order to perform record-oriented, as opposed to stream-oriented I/O, some sort of application-level record marking protocol needs to be employed (e.g. records delimited with newlines).

Flow Control

• When reading from a pipe, the `read` system call will block until there are some data available. It will then return any and all available data (up to limit specified by the caller

as the third argument to read), and will not wait until an entire buffer full of data are available. [We are ignoring non-blocking I/O options for now.]
• Each pipe is a FIFO of a specific capacity, which is system-dependent and possibly controllable by the system administrator. A typical FIFO size is 64K. If there is insufficient room in the FIFO to handle the entire write request, the write will block until there is room. This provides the "back pressure" against the writing process to create "flow control" and throttle a fast writer piping to a slow reader. (Again, we are ignoring non-blocking I/O options at this time. Non-blocking behavior can be specified for pipes using the `fcntl` system call. This is beyond the scope of this unit.)

Atomicity, Interrupted read/write, Short Writes

If the write request size is 4K or less, the write will be handled **atomically**, and, in the event that there are multiple processes writing to the same pipe, these atomic writes will be preserved and not interleaved. However, if the write request size exceeds 4K, the write will be broken up into smaller chunks of 4K, and could potentially be interleaved with other 4K chunks from other writers. However, pipes are rarely used in this fashion.

Unless non-blocking I/O is being used, a write system call to a pipe blocks until the entire requested amount has made it into the pipe. For example, let's say the pipe is completely full, and a process does `write(pipe_wrfd,buf,65536)` then after some period of time, the reader drains off 4096 bytes. Under this scenario, the write system call does **not** return 4096. The process remains sleeping. When the 65536th byte has been written into the pipe, then write returns, with a return value of 65536. If a programmer had written bad code that doesn't correctly handle "short writes" there is no harm here, just as short writes won't generally happen when writing to ordinary files on disk.

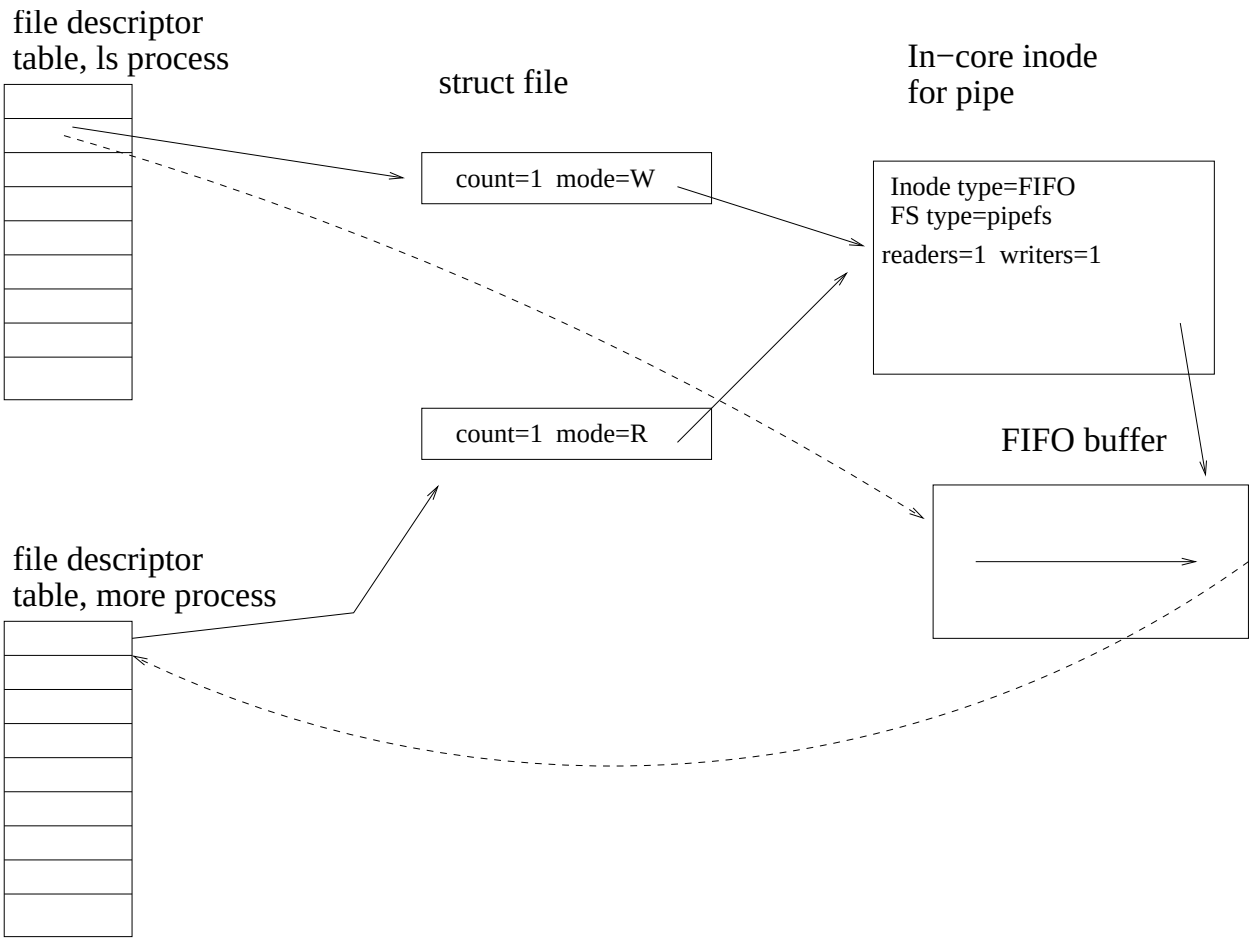
However, things get much uglier if signal handlers are involved. Let us repeat this scenario. The reader drains 4096 bytes and this allows the writer to move 4096 bytes into the pipe. At this point, a signal arrives. Since waiting for pipe read/write is considered a "long" sleep, it is interruptible, and the signal wakes up the writer. What is the poor kernel to do? Since 4096 of the 65536 bytes have been written into the pipe, the kernel can't ignore that fact and mislead the caller of the write system call by returning a 0 or -1, both of which would indicate that nothing was written. So, there is no choice but to return 4096. Here is a case where a bad programmer could get a rude lesson in partial writes!

But what if no bytes had made it into the pipe prior to the signal arrival? Now the Linux kernel has options: (1) if the SA_RESTART flag is set in the signal handling table for the signal number that was received, upon return from the user-level signal handler, the kernel will restart the write system call, with the identical parameters (i.e. with the same buffer address and the same write request count). This is fine since nothing actually happened during the first write system call. The process will return back to sleep until the write completes. (2) if SA_RESTART is not set, the kernel causes the write system

call to return EINTR. After the signal handler returns, execution of the program resumes at the point of returning from the write system call, the return value is -1, and errno is EINTR.

Connection Control

• When the write side of the pipe closes (there are no more open file descriptors in any processes referring to it), this generates an EOF condition. Once any pending data have been read out of the FIFO, all subsequent reads will return 0.
• When the read side of the pipe closes, this condition is known as a **broken pipe**. Any pending data in the FIFO are discarded. An attempt to write to a broken pipe (including a previous write which is sleeping waiting on a full pipe) will result in the failure of the write system call with EPIPE. A signal (SIGPIPE) will also be delivered to the writer process. The default action of SIGPIPE is to terminate the process. This ensures that a program which is poorly written and does not error check the `write` system call doesn't continue to try to push data into the broken pipe forever.
• In order to preserve this behavior with respect to EOF and SIGPIPE/EPIPE, it is important to close any extraneous file descriptors that might be hanging on to the read or write side of a pipe, especially during dups and forks.
• An interesting "feature" that occurs with broken pipes is that if the pipe is partially filled and then the reader side is closed, this will **not** generate an error on `close` on the write side. This would appear to be a design flaw, in that data loss would be undetectable from the writing process's view. However, the presumption is that a parent process invoked both the reader and the writer and connected them with a pipeline. The abnormal exit of the reader process would be detected by the parent (through the `wait` system call) which would then report the failure of the pipeline as a whole.
• The figure below illustrates a writer process (ls) connected to a reader process (more) via a pipe.



Named Pipes

Pipes created with the `pipe` system call do not have any associated pathname in the filesystem namespace. This means that the only access is through the file descriptors; it is not possible to use `open` to gain access. Thus, the only way two processes can communicate using a pipe is if they share a common ancestor.

A **named pipe** is identical to a regular pipe, but it is accessed through a node in the filesystem having type `S_IFIFO`. A named pipe is sometimes called a FIFO. To create this special node one can use the `mknod` system call:

```
if (mknod("/tmp/namedpipe",S_IFIFO|0600,0)<0)
{
        perror("unable to create named pipe /tmp/namedpipe");
}
```

```
$ ./a.out
$ ls -l /tmp/namedpipe
```

```
prw-------    1 hak      root            0 Sep 25 23:12 /tmp/namedpipe
```

In the example above, the leading "p" in the ls output identifies the created inode as a named pipe (IFIFO). Note that the permissions mode is bitwise-OR'd.

The FIFO inode can also be created from the command prompt using the `mknod` or `mkfifo` command.

Semantics of named pipes are slightly different from anonymous pipes. Since the named pipe is opened with `open`, it can be opened read-only, write-only or read/write (i.e. `O_RDONLY`, `O_WRONLY`, `O_RDWR`). There can be more than one opening of the pipe too (i.e. multiple `struct file` in the kernel). When a named pipe is opened read-only, the open system call blocks until there is at least one instance of the same pipe being opened for writing (or read/write). Likewise, a write-only open blocks waiting for readers. A read/write open always succeeds immediately.

`read` from a named pipe returns whatever data are currently in the FIFO, or blocks if there are no data, just like anonymous pipes. If there are no writers, read returns 0 (after returning any pending data). But unlike an anonymous pipe, this EOF-like condition is not permanent. If another writer appears, future reads may return additional data. In the meantime, all reads would return 0. Because this condition results in a "spin loop," it is better practice to close the read side of the named pipe upon an EOF condition, and then re-open it. The open will then block until another writer comes along.

Likewise, a write to a named pipe with no readers results in either a `SIGPIPE` or `EPIPE`, just like anonymous pipes. Furthermore, the same kind of non-blocking options can be applied.

Named pipes can be used as a means of inter-process communication among unrelated processes on the same local system. They can be used as a command/control channel to connect with "daemon" processes that are running in the background, disconnected from any controlling terminal.