UNIX Network Programming

Overview of STREAMS

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STREAMS Overview

- STREAMS is a flexible communication subsystem framework
  - Originally developed by Dennis Ritchie for Research UNIX
- STREAMS provides a uniform infrastructure for developing and configuring character-based I/O
  - *e.g.*, networks, terminals, local IPC
- STREAMS supports the addition and removal of processing components at installation-time or run-time
  - Via user-level or kernel-level commands

STREAMS Overview (cont'd)

- The STREAMS paradigm is *data-driven*, not *demand-driven*
  - *i.e.*, asychronous in the kernel, yet synchronous at the application
- Supports both *immediate* and *deferred* processing
- Internally, data are transferred by passing pointers to messages
  - Goal is to reduce memory-to-memory copying overhead

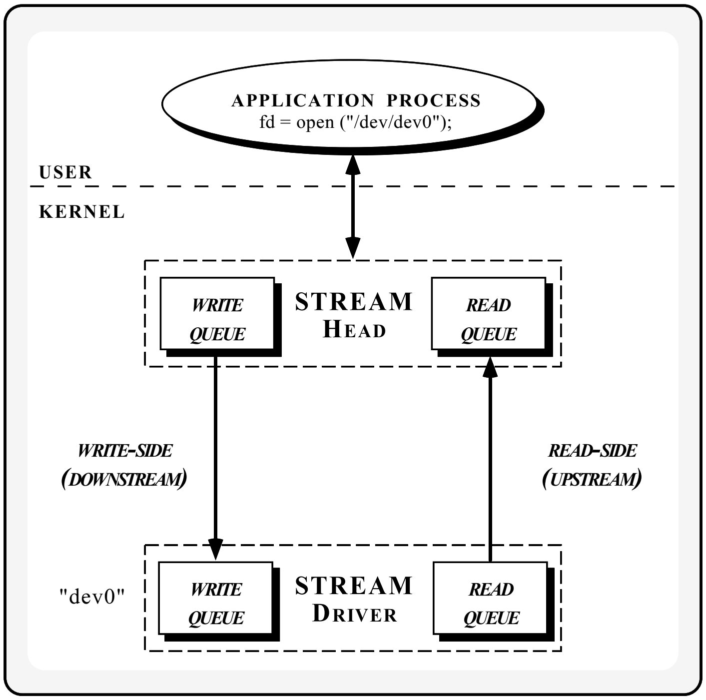
STREAMS Benefits

- STREAMS provides an integrated environment for developing kernel-resident networking services
- STREAMS promotes definition of standard *service interfaces*
  - *e.g.*, TPI and DLPI
- STREAMS supports dynamic "service substitution" controlled by user-level commands

STREAMS Benefits (cont'd)

- Message-based interfaces enable off-board protocol migration
- Permits layered and de-layered multiplexing
- More recent implementations take advantage of parallelism in the operating system and hardware

A Simple Stream



APPLICATION PROCESS
fd = open ("/dev/dev0");

USER

KERNEL

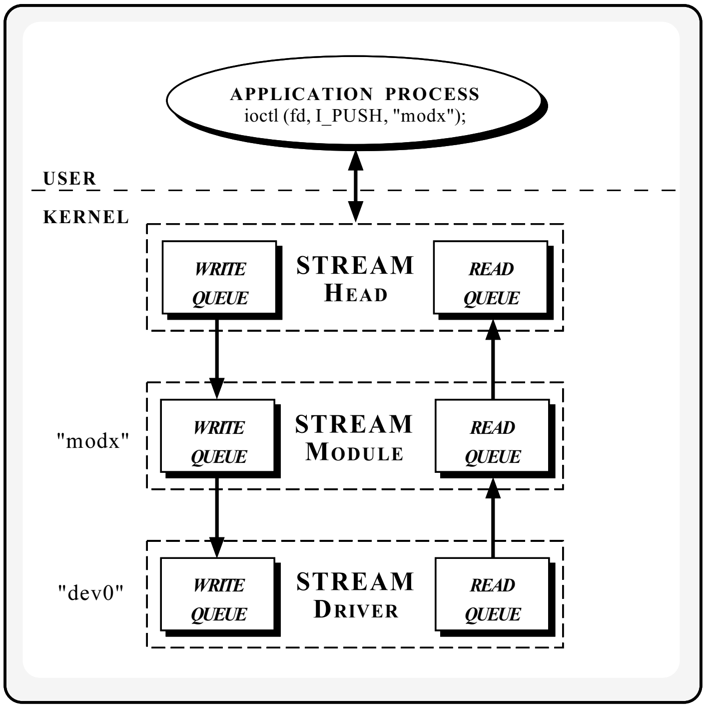
WRITE QUEUE **STREAM HEAD** *READ QUEUE*

WRITE-SIDE (DOWNSTREAM)

READ-SIDE (UPSTREAM)

"dev0" *WRITE QUEUE* **STREAM DRIVER** *READ QUEUE*

A Module on a Stream



APPLICATION PROCESS
ioctl (fd, I_PUSH, "modx");

USER

KERNEL

WRITE QUEUE **STREAM HEAD** *READ QUEUE*

"modx" *WRITE QUEUE* **STREAM MODULE** *READ QUEUE*

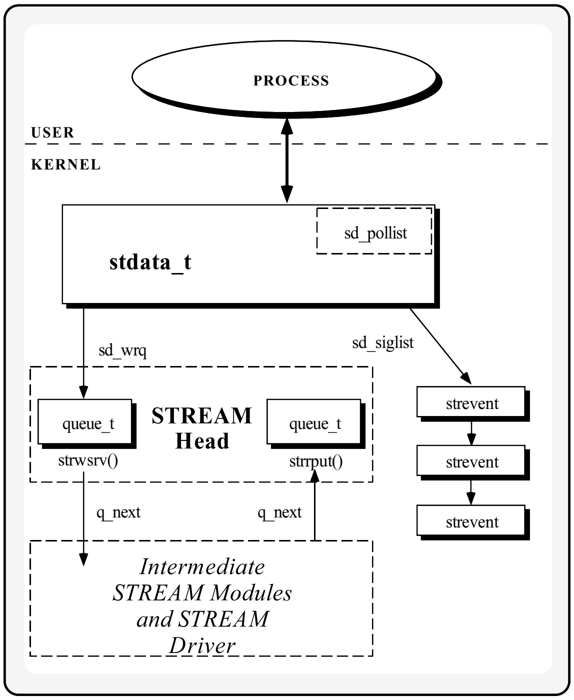
"dev0" *WRITE QUEUE* **STREAM DRIVER** *READ QUEUE*

The Stream Head

- A "stream head" exports a uniform service interface to other layers of the UNIX kernel
  - Including the application "layer" running in user-space
- General stream head services include

1. Queueing
   (a) Provides a synchronous interface to asychronous devices
2. Datagram- and stream-oriented data transfer
3. Segmentation and reassembly of messages
4. Event propagation
   - *i.e.*, signals

The Stream Head (cont'd)



The Stream Head (cont'd)

- Stream head operations include
  - **stropen()**
    - ▷ called from file system layer to open a Stream
  - **strclean()**
    - ▷ called from file system layer to remove event cells from Stream Head when a file is closed
  - **strclose()**
    - ▷ called from the file system layer to dismantle a Stream
  - **strread()**
    - ▷ called from the file system layer to retrieve data messages coming *upstream*

- Stream Head operations (cont'd)
  - **strwrite()**
    - ▷ called from the file system layer to send data messages *downstream*
  - **strioctl()**
    - ▷ called from the file system layer to perform control operations
  - **strgetmsg()**
    - ▷ called from the system call layer to get a protocol or data message coming *upstream*
  - **strputmsg()**
    - ▷ called from the system call layer to send a protocol or data message *downstream*
  - **strpoll()**
    - ▷ called from the file system layer to check if pollable events are satisfied

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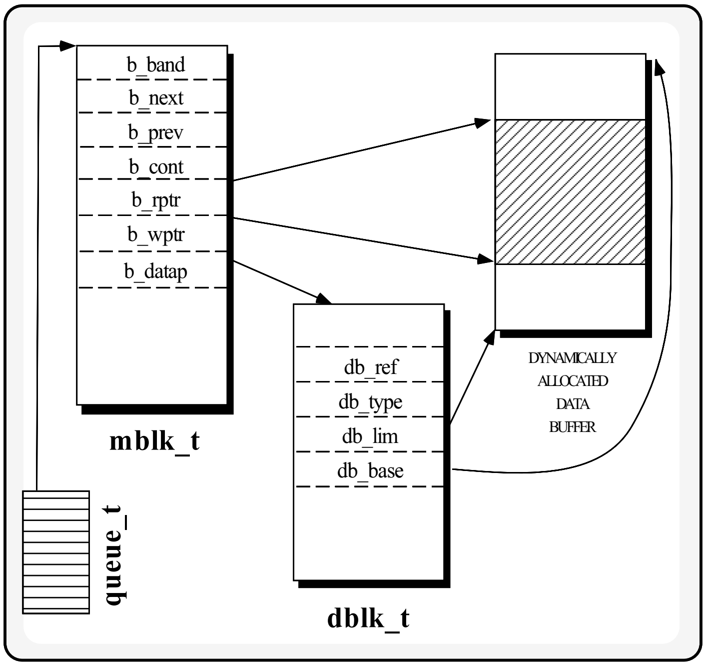
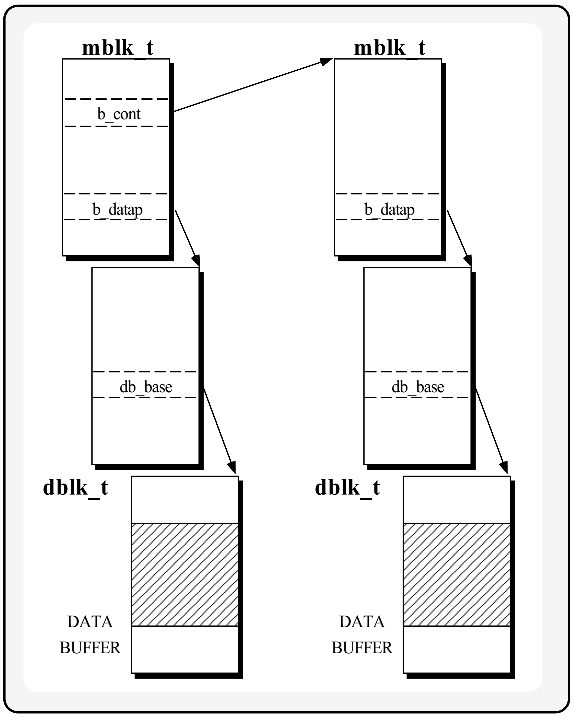
Messages

- In STREAMS, all information is exchanged via messages
  - *i.e.*, both data and control messages of various priorities
- A multi-component message structure is used to reduce the overhead of
  1. Memory-to-memory copying
     - *i.e.*, via "reference counting"
  2. Encapsulation/de-encapsulation
     - *i.e.*, via "composite messages"
- Messages may be queued at STREAM modules

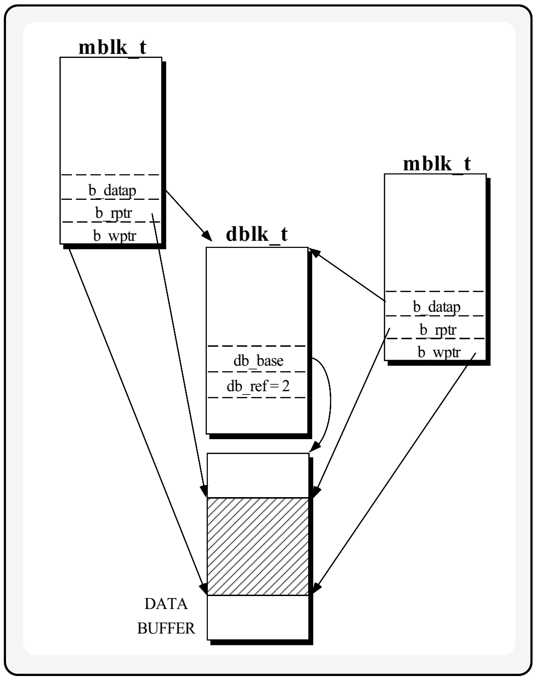
Message Structure



Composite Message



Message Buffer Sharing



STREAMS Message Types

M_DATA	user data
M_PROTO	protocol information
M_PASSFP	pass file pointer
M_IOCTL	user ioctl() request
M_BREAK	request line break
M_SIG	signal process group
M_DELAY	request transmit delay
M_CTL	module-specific control message
M_SETOPTS	set Stream head options
M_RSE	reserved for RSE use

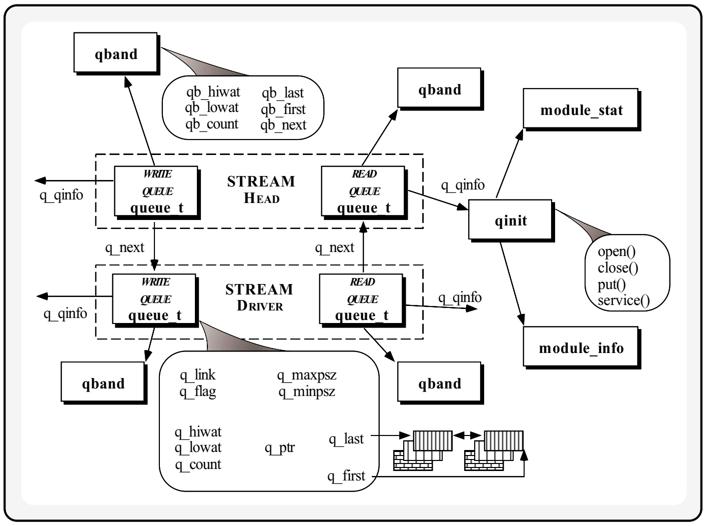
- *Normal* priority messages
  - M_DATA, M_PROTO, M_PASSFP, and M_IOCTL may be generated from user-level
  - Typically subject to flow control

STREAMS Message Types (cont'd)

M_PCPROTO	protocol information
M_FLUSH	flush queues
M_IOCACK	acknowledge ioctl() request
M_IOCNAK	fail ioctl() request
M_COPYIN	request to copyin ioctl() data
M_COPYOUT	request to copyout ioctl() data
M_IOCDATA	reply to M_COPYIN and M_COPYOUT
M_PCSIG	signal process group
M_READ	read notification
M_HANGUP	line disconnect
M_ERROR	fatal error
M_STOP	stop output immediately
M_START	restart output
M_STOPI	stop input immediately
M_STARTI	restart input
M_PCRSE	reserved for RSE use

- *High* priority messages
  * Typically *not* flow controlled
  * M_PCPROTO may be generated from user-level
  * Others passed between STREAM components

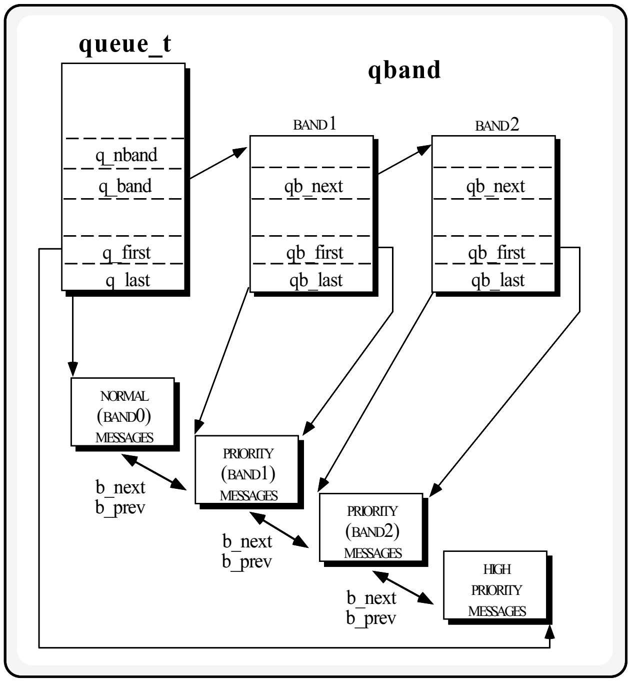
Queue Structure



Queue Structure (cont'd)

- `queue_t`
  - Primary data structure
    - Each module contains a write queue and a read queue
  - Stores information on flow control, scheduling, max/min interface sizes, linked messages, private data
- `qinit`
  - Contains `put()`, `service()`, `open()`, `close()` subroutines
- `qband`
  - Contains information on each additional message band > 0 and < 256
- `module_info`
  - Stores default flow control information

Queue and Message Linkage



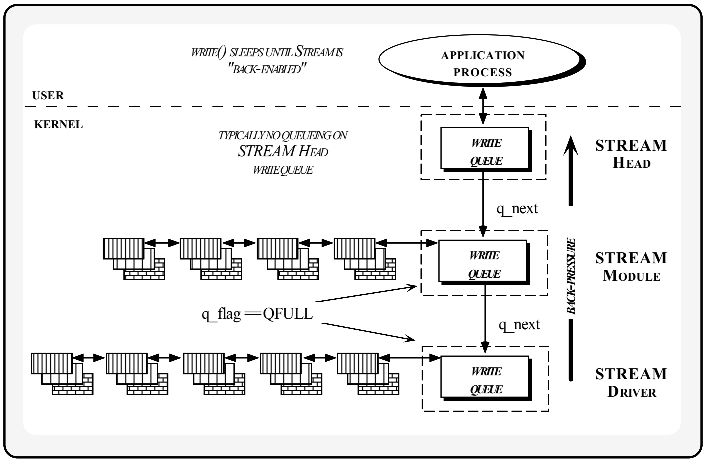
Queue Subroutines

- Four standard subroutines are associated with queues in a module or driver, *e.g.*,
  - `open`(queue_t *q, dev_t *devp, **int** oflag, **int** sflag, cred_t *cred_p);
    - ▹ Called when Stream is first opened and on any subsequent opens
    - ▹ Passed a pointer to the new read queue
    - ▹ Also called any time a module is "pushed" onto the Stream
  - `close`(dev_t dev, **int** flag, **int** otyp, cred_t *cred_p);
    - ▹ Called when last reference to a Stream is closed
    - ▹ Also called when a module is "popped" off the Stream

Queue Subroutines (cont'd)

- Standard subroutines (cont'd)
  - `put(queue_t *q, mblk_t *mp)`
    - ▹ Performs *immediate* processing
    - ▹ Supports synchronous communciation services
      - · *i.e.*, further `queue` processing is blocked until `put()` returns
  - `service(queue_t *q)`
    - ▹ Performs *deferred* processing
    - ▹ Supports asynchronous communication services
      - · Uses the message queue available in a `queue`
    - ▹ Runs as a "weightless" process...

Queue Flow Control



- `put()` and `service()` work together to support advisory flow control

Flow Control and the service() Procedure

- Typical *non-multiplexed* example

```
int service (queue_t *q)
{
     mblk_t *mp;

     while ((mp = getq (q)) != 0)
          if (queclass (mp) == QPCTL ||
               canputnext (q)) {
               /* Process message */
               putnext (q, mp);
          }
          else {
               putbq (q, mp);
               return 0;
          }
}
```

- Flow control is more complex with multiplexers and concurrency

Flow Control and the canput() Procedure

- `canputnext()` is used by `put()` and `service()` routines to test advisory flow control conditions

- *e.g.*,

```
int canputnext (queue_t *q)
{
      find closest queue with a service() procedure
      if (queue is full) {
            set flag for "back-enabling"
            return 0;
      }
      return 1;
}
```

- Note that non-MP systems may use `canput()`...

Flow Control and the put() Procedure

- Typical `put()` example

```
int put (queue_t *q, mblk_t *mp)
{
      if (queclass (mp) == QPCTL ||
            canputnext (q)) {
            /* Process message */
            putnext (q, mp);
      else
            putq (q, mp);
            /* Enables service routine */
      return 0;
}
```

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putq()

- The `int putq(queue_t *, mblk_t *)` function enqueues a message on a queue
  - It is typically called by a queue's `put()` procedure when it can no longer proceed...

- `putq()` automatically handles
  1. priority-band allocation
  2. priority-band message insertion
  3. flow control

- Enqueueing a high priority message automatically schedules the queue's `service()` procedure to run at some point
  - Differs on MP vs. non-MP system

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getq()

- The `mblk_t *getq(queue_t *)` function dequeues a message from a queue
  - It is typically called by a queue's `service()` procedure

- Messages are dequeued in priority order
  - *i.e.*, higher priority messages are stored first in the queue!

- `getq()` handles
  1. Flow control
  2. Back-enabling

- `getq()` returns 0 when there are no available messages

Multiplexing

- STREAMS provides rudimentary support for multiplexing via `multiplexor drivers`
  - Unlike modules, multiplexors occupy a file-system node that can be “opened”
    - ▷ Rather than “pushed”
- Multiplexors may contain one or more upper and/or lower connections to other STREAM modules and/or multiplexors
  - Enables support for layered network protocol suites
    - ▷ *e.g.*, "/dev/tcp”
- Note there is no automated support for propagating flow control across multiplexors

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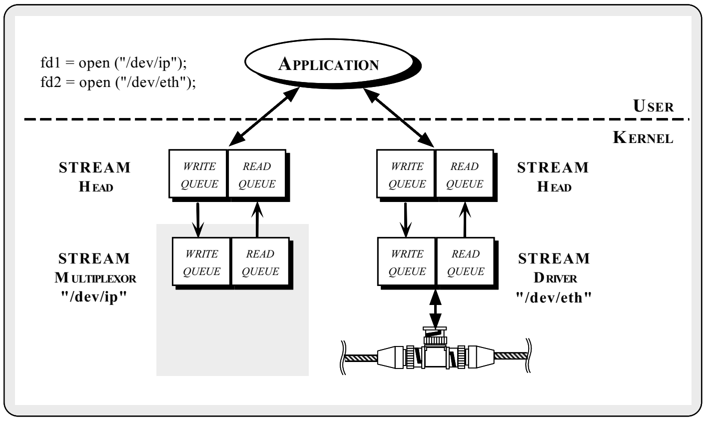
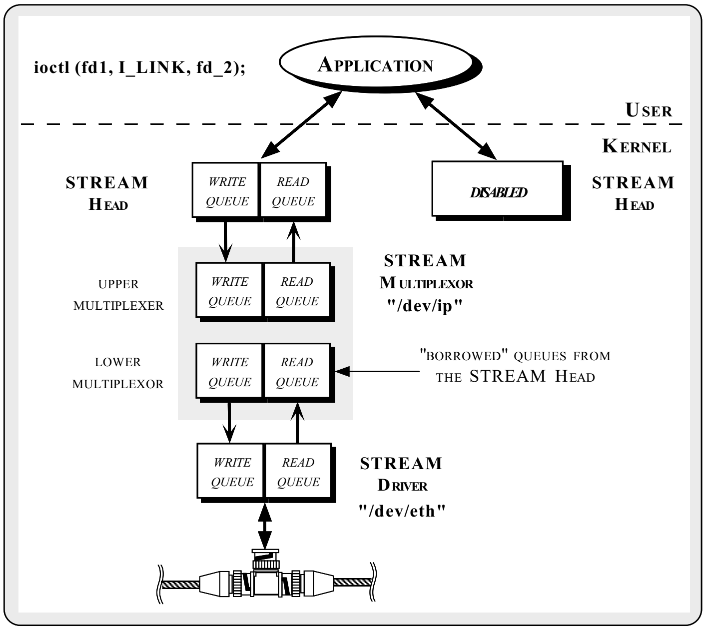
Multiplexor Links (before)



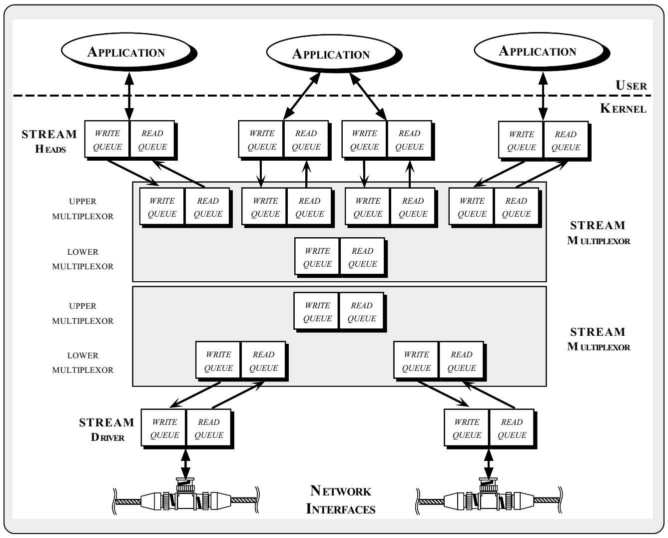
```
fd1 = open ("/dev/ip");
fd2 = open ("/dev/eth");
```

Multiplexor Links (after)

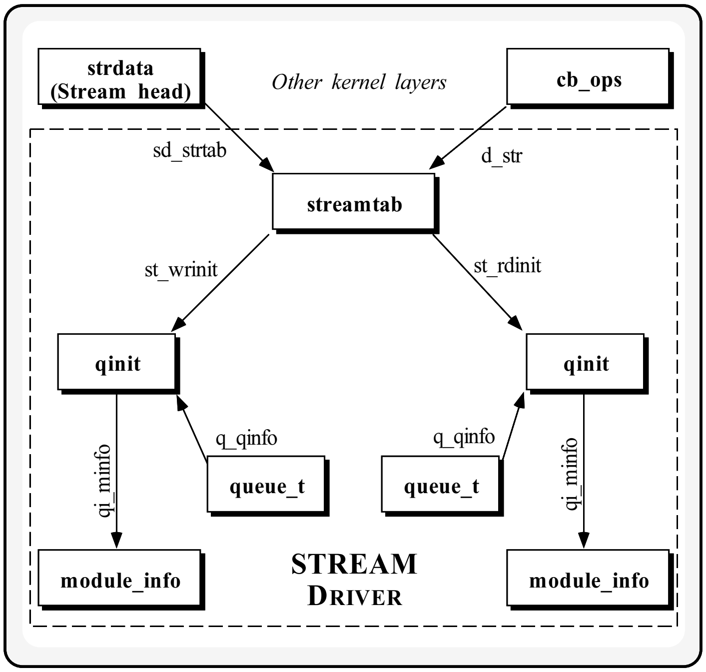


```
ioctl (fd1, I_LINK, fd_2);
```

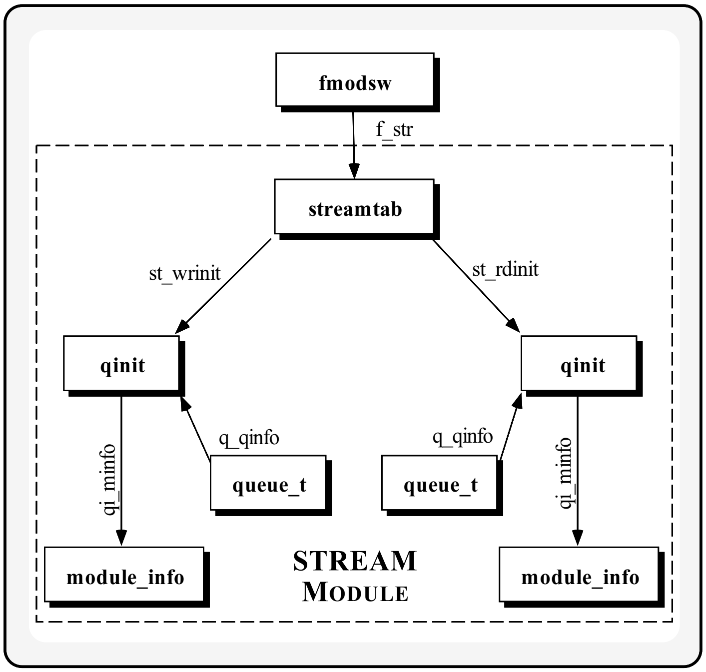
Internetworking Multiplexor



Driver Data Structure Linkage



Module Data Structure Linkage

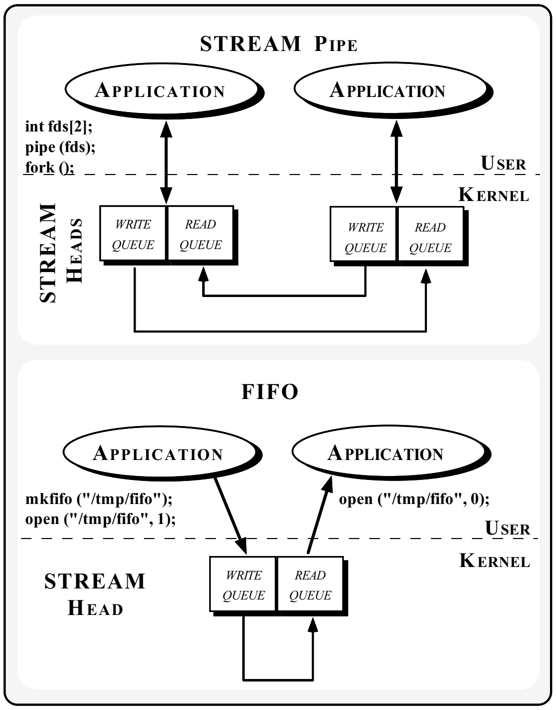


Pipes and FIFOs

- In SVR4 and Solaris, the traditional local IPC mechanisms such as pipes and FIFOs have been reimplemented using STREAMS

- This has broaded the semantics of pipes and FIFOs in the following ways:
  1. Pipes are now bidirectional (STREAM pipes)
  2. Pipes and FIFOs now support both bytestream-oriented and message-oriented communication
     - `ioctl()s` exist to modify the behavior of STREAM descriptors to enable or disable many of the new features
  3. Pipes can be explicitly named and exported into the file system
  4. Pipes and FIFOs can be extended by having modules pushed onto them

Pipes and FIFOs (cont'd)



```
int fds[2];
pipe (fds);
fork ();
```

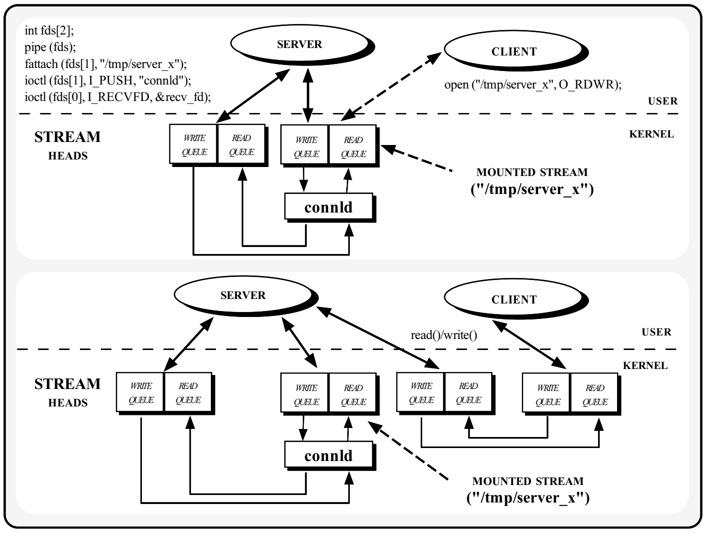
```
mkfifo ("/tmp/fifo");
open ("/tmp/fifo", 1);
```

```
open ("/tmp/fifo", 0);
```

Mounted Streams and CONNLD

- In earlier generations of UNIX, pipes were restricted to allowing multiplexed communication
  - This is overly complex for many client/server-style applications
- SVR4 UNIX and Solaris provide a mechanism known as “Mounted Streams” that permits non-multiplexed communication
  - This provides semantics similar to UNIX domain sockets
  - However, Mounted Streams are more flexible since they incorporate other features of STREAMS

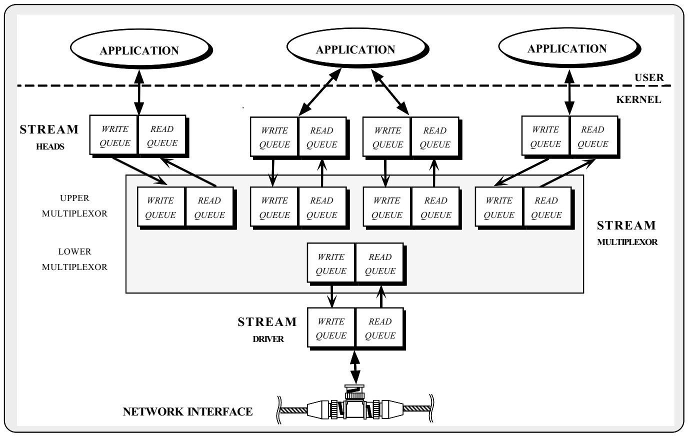
Mounted Streams and CONNLD (cont’d)



```
int fds[2];
pipe (fds);
fattach (fds[1], "/tmp/server_x");
ioctl (fds[1], I_PUSH, "connld");
ioctl (fds[0], I_RECVFD, &recv_fd);
```

```
open ("/tmp/server_x", O_RDWR);
```

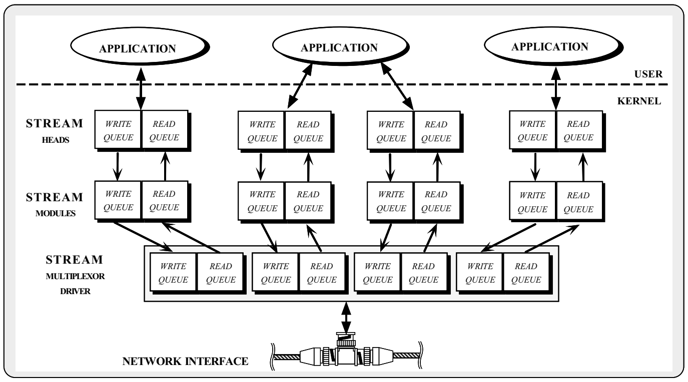
Layered Multiplexing



Layered Multiplexing (cont’d)

- *Advantages*
  - Share resources such as control blocks
  - Supports standard OSI and Internet layering models
- *Disadvantages*
  - More processing involved to demultiplex in deep protocol stacks
  - May be more difficult to parallelize due to locks and shared resource contention
  - Hard to propagate flow control and QOS info across muxer

De-layered Multiplexing



De-layered Multiplexing (cont'd)

- *Advantages*
  - Less processing for deep protocol stacks
  - Potentially increased parallelism due to less contention and locking required
  - Easier to propagate flow control and QOS info
- *Disadvantages*
  - Violates layering (*e.g.*, need a packet filter)
  - Replicates resources such as control blocks

STREAM Concurrency

- Modern versions of STREAMS support multiprocessing
  - Since modern UNIX systems have multi-threaded kernels
- Different levels of concurrency support include
  1. *Fine-grain*
     * Queue-level
     * Queue-pair-level
  2. *Coarse-grain*
     * Module-level
     * Module-class-level
     * Stream-level
- Note, developers must use kernel locking primitives to provide mutual exclusion and synchronization

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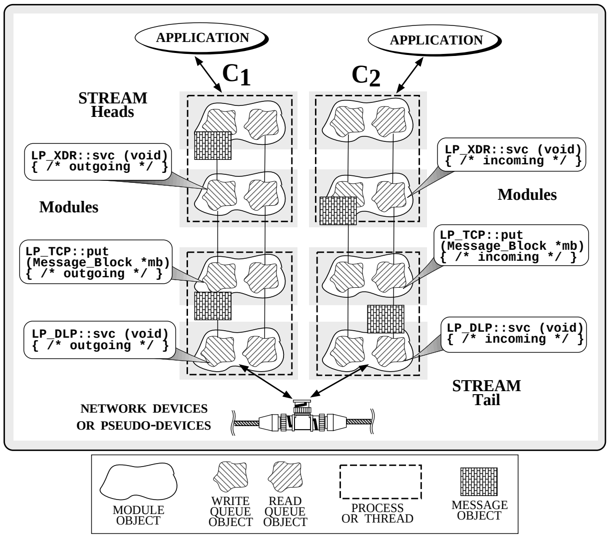
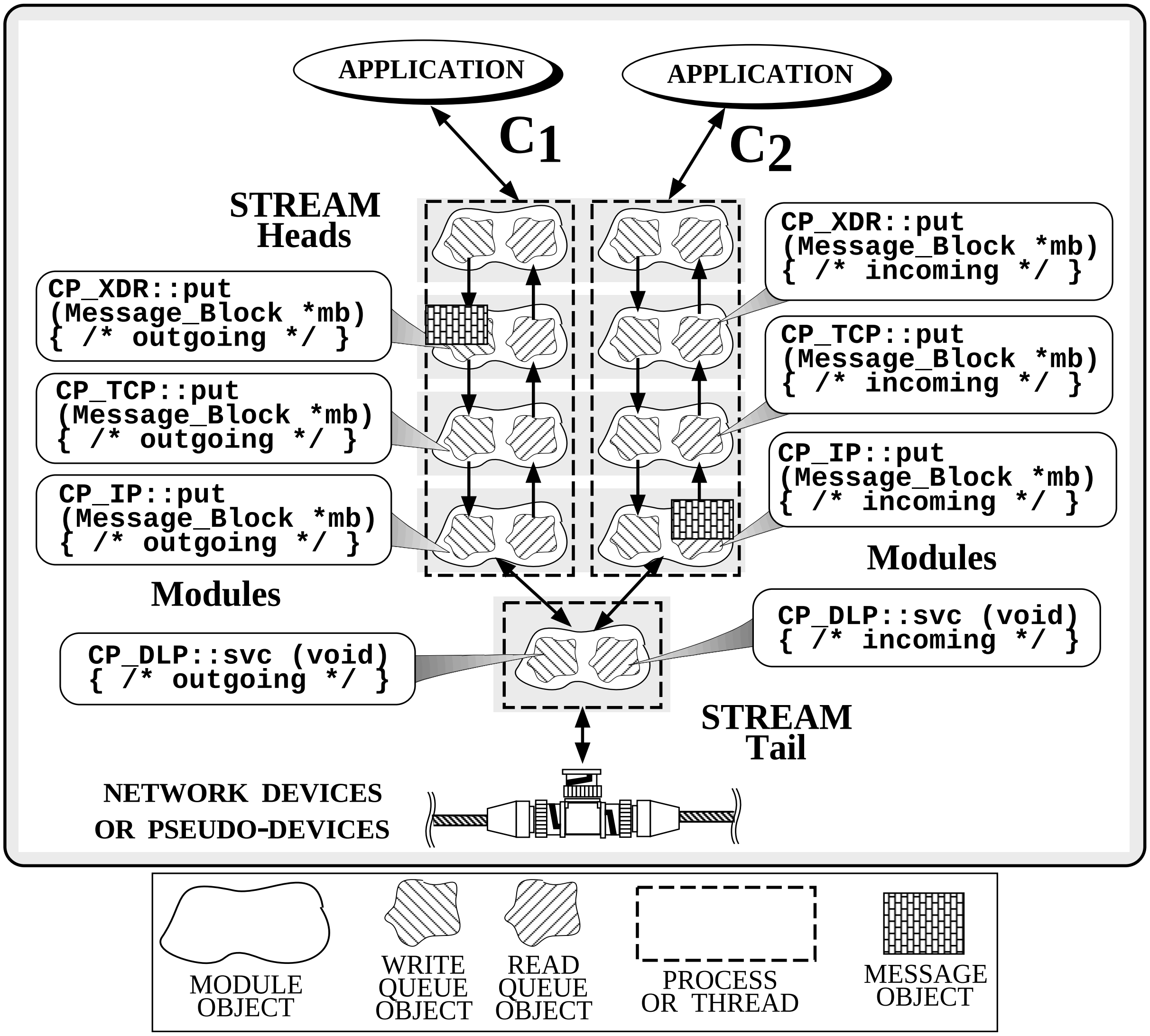
Concurrency Alternatives



```
LP_XDR::svc (void)
{ /* outgoing */ }
LP_TCP::put
(Message_Block *mb)
{ /* outgoing */ }
LP_DLP::svc (void)
{ /* outgoing */ }
LP_XDR::svc (void)
{ /* incoming */ }
LP_TCP::put
(Message_Block *mb)
{ /* incoming */ }
LP_DLP::svc (void)
{ /* incoming */ }
```

- Layer Parallelism

Concurrency Alternatives (cont'd)



```
CP_XDR::put
(Message_Block *mb)
{ /* outgoing */ }
```

```
CP_TCP::put
(Message_Block *mb)
{ /* outgoing */ }
```

```
CP_IP::put
(Message_Block *mb)
{ /* outgoing */ }
```

```
CP_DLP::svc (void)
{ /* outgoing */ }
```

```
CP_XDR::put
(Message_Block *mb)
{ /* incoming */ }
```

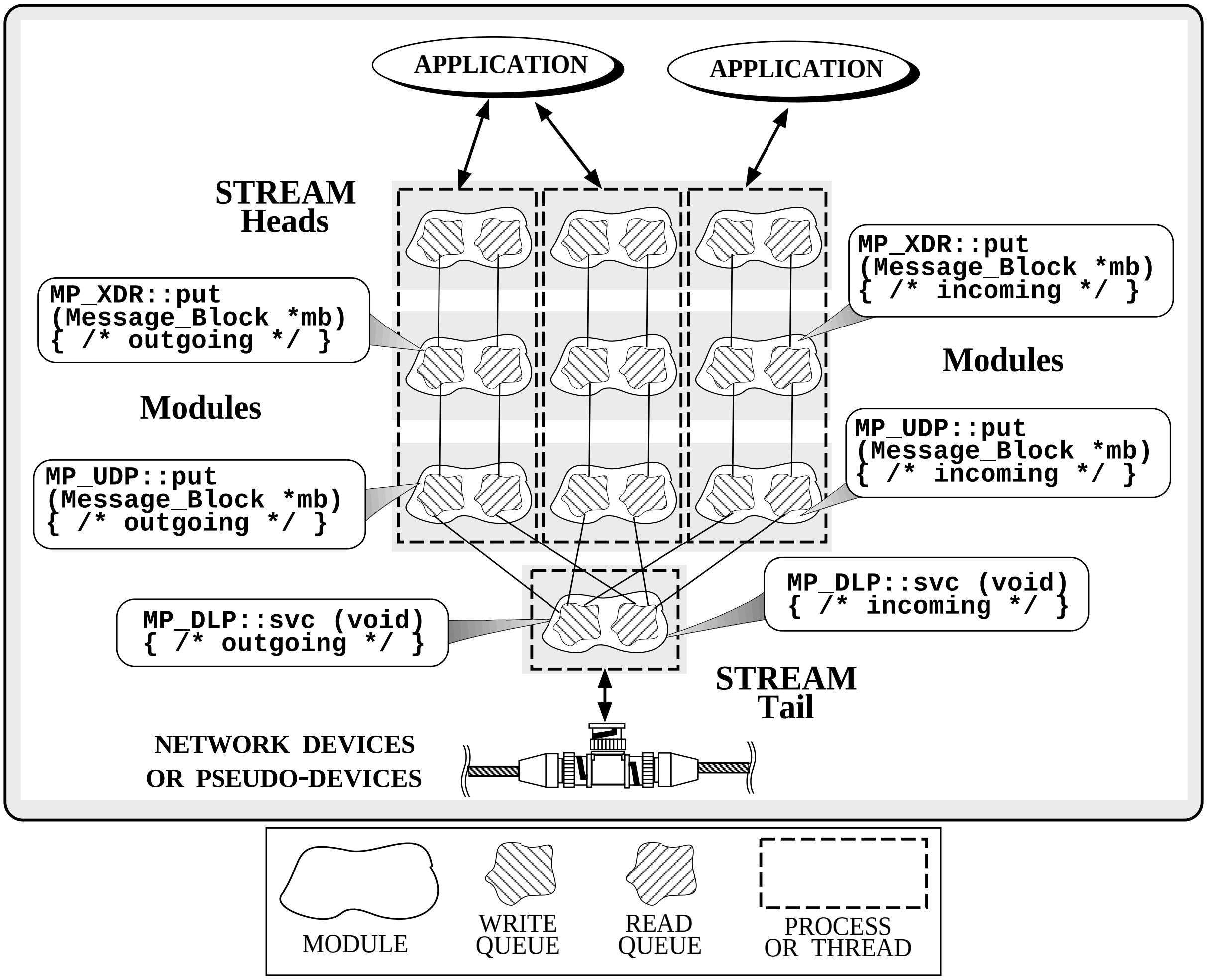
```
CP_TCP::put
(Message_Block *mb)
{ /* incoming */ }
```

```
CP_IP::put
(Message_Block *mb)
{ /* incoming */ }
```

```
CP_DLP::svc (void)
{ /* incoming */ }
```

- Connectional Parallelism

Concurrency Alternatives (cont'd)



- Message Parallelism

STREAMS Evaluation

- *Advantages*
  - Portability, availability, stability
  - Kernel-mode efficiency

- *Disadvantages*
  - Stateless process architecture
    - ▷ *i.e.*, cannot block!
  - Lack of certain support tools
    - ▷ *e.g.*, standard demultiplexing mechanisms
  - Kernel-level development environment
    - ▷ Limited debugging support...
  - Lack of real-time scheduling for STREAMS processing...
    - ▷ Timers may be used for “isochronous” service

Summary

- STREAMS provides a flexible communication framework that supports dynamic configuration and reconfiguration of protocol functionality

- Module interfaces are well-defined and reasonably well-documented

- Support for multi-processing exists in Solaris 2.x