Programmation Systèmes
Cours 9 — UNIX Domain Sockets

Stefano Zacchiroli
zack@pps.univ-paris-diderot.fr

Laboratoire PPS, Université Paris Diderot

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Outline

1. Sockets
2. Stream sockets
3. UNIX domain sockets
4. Datagram sockets

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1. Sockets
2. Stream sockets
3. UNIX domain sockets
4. Datagram sockets

Sockets

Sockets are IPC objects that allow to exchange data between processes running:

- either on the same machine (*host*), or
- on different ones over a network.

The UNIX socket API first appeared in 1983 with BSD 4.2. It has been finally standardized for the first time in POSIX.1g (2000), but has been ubiquitous to every UNIX implementation since the 80s.

Disclaimer

The socket API is best discussed in a network programming course, which this one is *not*. We will only address enough general socket concepts to describe how to use a specific socket family: UNIX domain sockets.

Client-server setup

Let's consider a typical client-server application scenario — no matter if they are located on the same or different hosts.

Sockets are used as follows:

- each application: create a socket
  - idea: communication between the two applications will flow through an imaginary "pipe" that *will* connect the two sockets together
- server: bind its socket to a well-known address
  - we have done the same to set up *rendez-vous* points for other IPC objects, e.g. FIFOs
- client: locate server socket (via its well-known address) and "initiate communication"[1] with the server

[1] various kinds of communication are possible, so we will refine this later

Socket bestiary

Sockets are created using the socket syscall which returns a file descriptor to be used for further operations on the underlying socket:

```
fd = socket(domain, type, protocol);
```

Each triple ⟨domain, type, protocol⟩ identifies a different "species" of sockets.

For our purposes `protocol` will always be 0, so we don't discuss it further.

Communication domains

Each socket exists within a communication domain.

Each communication domain determines:

- how to identify a socket, that is the syntax and semantics of socket well-known addresses
- the communication range, e.g. whether data flowing through the socket span single or multiple hosts

Popular socket communication domains are:

- **UNIX** communication within the same machine, using pathnames as addresses
- **IPv4** communication across hosts, using IPv4 addresses (e.g. `173.194.40.128`)
- **IPv6** communication across hosts, using IPv6 addresses (e.g. `2a00:1450:4007:808::1007`)

Communication domains — details

domain[2]	range	transport	address format	address C struct
AF_UNIX	same host	kernel	pathname	sockaddr_un
AF_INET	any host w/ IPv4 connectivity	IPv4 stack	32-bit IPv4 address + 16-bit port number	sockaddr_in
AF_INET6	any host w/ IPv6 connectivity	IPv6 stack	128-bit IPv6 address + 16-bit port number	sockaddr_in6

fd = socket(domain, type, protocol);

[2] value for the first argument of the socket syscall

Socket types

```
fd = socket(domain, type, protocol);
```

Within each socket domain you will find multiple socket types, which offer different IPC features:

feature	socket type SOCK_STREAM	socket type SOCK_DGRAM
reliable delivery	yes	no
message boundaries	no	yes
connection-oriented	yes	no

Stream sockets (SOCK_STREAM)

Stream sockets provide communication channels which are:

- byte-stream: there is no concept of message boundaries, communication happens as a continuous stream of bytes
- reliable: either data transmitted arrive at destination, or the sender gets an error
- bidirectional: between two sockets, data can be transmitted in either direction
- connection-oriented: sockets operate in connected pairs, each connected pair of sockets denotes a communication context, isolated from other pairs
  - a peer socket is the other end of a given socket in a connection
  - the peer address is its address

Intuition

Stream sockets are like pipes, but also permit (in the Internet domains) communication across the network.

Datagram sockets (SOCK_DGRAM)

Datagram sockets provide communication channels which are:

- message-oriented: data is exchanged at the granularity of messages that peers send to one another; message boundaries are preserved and need not to be created/recognized by applications
- non-reliable: messages can get *lost*. Also:
  - messages can arrive *out of order*
  - messages can be *duplicated* and arrive multiple times

  It is up to applications to detect these scenarios and react (e.g. by re-sending messages after a timeout, add sequence number, etc.).
- connection-less: sockets do not need to be connected in pairs to be used; you can send a message to, or receive a message from a socket without connecting to it beforehand

TCP & UDP (preview)

In the Internet domains (AF_INET and AF_INET6):

- socket communications happen over the IP protocol, in its IPv4 and IPv6 variants (Internet layer)
- stream sockets use the TCP protocol (transport layer)
- datagram sockets use the UDP protocol (transport layer)

You'll see all this in the network programming course...

netstat(8)

```
$ netstat -txun

Active Internet connections (w/o servers)
Proto Recv-Q Send-Q Local Address           Foreign Address         State
tcp        1      1 128.93.60.82:53161      98.137.200.255:80       LAST_ACK
tcp        0      0 10.19.0.6:54709         10.19.0.1:2777          ESTABLISHED
tcp        0      0 128.93.60.82:53366      98.137.200.255:80       ESTABLISHED
tcp        0      0 10.19.0.6:46368         10.19.0.1:2778          ESTABLISHED
tcp        0      0 128.93.60.82:47218      74.125.132.125:5222     ESTABLISHED
tcp6       1      0 ::1:51113               ::1:631                 CLOSE_WAIT
udp        0      0 127.0.0.1:33704         127.0.0.1:33704         ESTABLISHED

Active UNIX domain sockets (w/o servers)
Proto RefCnt Flags       Type       State         I-Node   Path
unix  2      [ ]         DGRAM                    23863    /var/spool/postfix/dev/log
unix  2      [ ]         DGRAM                    1378     /run/systemd/journal/syslog
unix  2      [ ]         DGRAM                    1382     /run/systemd/shutdownd
unix  2      [ ]         DGRAM                    4744     @/org/freedesktop/systemd1/notify
unix  5      [ ]         DGRAM                    1390     /run/systemd/journal/socket
unix  28     [ ]         DGRAM                    1392     /dev/log
unix  3      [ ]         STREAM     CONNECTED     138266
unix  2      [ ]         STREAM     CONNECTED     79772
unix  3      [ ]         STREAM     CONNECTED     30935
unix  3      [ ]         STREAM     CONNECTED     23037
unix  3      [ ]         STREAM     CONNECTED     416650
unix  3      [ ]         SEQPACKET  CONNECTED     135740
unix  3      [ ]         STREAM     CONNECTED     26655    /run/systemd/journal/stdout
unix  2      [ ]         DGRAM                    22969
unix  3      [ ]         STREAM     CONNECTED     29256    @/tmp/dbus-tHnZVgCvqF
unix  3      [ ]         STREAM     CONNECTED     91045    @/tmp/dbus-tHnZVgCvqF
...
```

Socket creation

Socket creation can be requested using socket:

```
#include <sys/socket.h>

int socket(int domain, int type, int protocol);
```

Returns: *file descriptor on success, -1 on error*

As we have seen, the 3 arguments specify the "species" of socket you want to create:

- `domain`: AF_UNIX, AF_INET, AF_INET6
- `type`: SOCK_STREAM, SOCK_DGRAM
- `protocol`: always 0 for our purposes[3]

The file descriptor returned upon success is used to further reference the socket, for both communication and setup purposes.

[3] one case in which it is non-0 is when using raw sockets

Binding sockets to a well-known address

To allow connections from other, we need to bind sockets to well-known addresses using `bind`:

```
#include <sys/socket.h>

int bind(int sockfd, const struct sockaddr *addr, socklen_t addrlen);
```

Returns: *0 on success, -1 on error*

- `sockfd` references the socket we want to bind
- `addrlen`/`addr` are, respectively, the length and the structure containing the well-known address we want to bind the socket to

The actual type of the addr structure depends on the socket domain...

Generic socket address structure

We have seen that the address format varies with the domain:

- UNIX domain uses pathnames
- Internet domains use IP addresses

But bind is a generic system call that can bind sockets in any domain! Enter struct sockaddr :

```
struct sockaddr {
    sa_family_t sa_family;    /* address family (AF_*) */
    char        sa_data[14];  /* socket address (size varies
                                 with the socket domain) */
}
```

- each socket domain has its own variant of sockaddr
- you will fill the domain-specific struct
- and cast it to struct sockaddr before passing it to bind
- bind will use sa_family to determine how to use sa_data

Outline

1 Sockets

2 Stream sockets

3 UNIX domain sockets

4 Datagram sockets

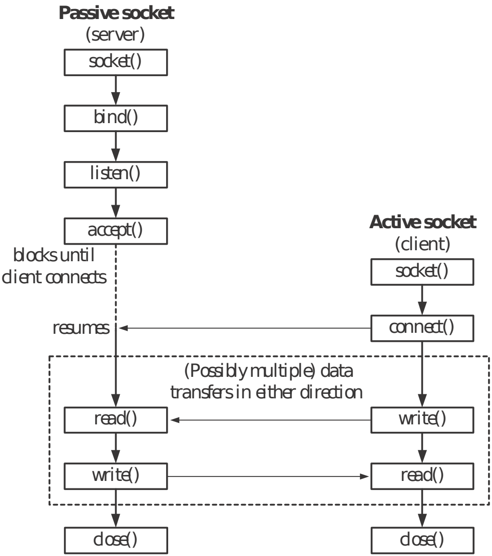
The phone analogy for stream sockets

Stream socket / phone analogy

To communicate one application—which we call "client"—must call the other—the "server"—over the phone. Once the connection is established, each peer can talk to the other for the duration of the phone call.

- both: `socket()` → install a phone
- server: `bind()` → get a phone number
- server: `listen()` → turn on the phone, so that it can ring
- client: `connect()` → turns on the phone and call the "server", using its number
- server: `accept()` → pick up the phone when it rings (or wait by the phone if it's not ringing yet)

Stream socket syscalls — overview



TLPI, Fig. 56-1

Terminology

"Server" and "client" are ambiguous terms. We speak more precisely of passive and active sockets.

- sockets are created active; `listen()` makes them passive
- connect() performs an active open
- accept() performs a passive open

Willingness to accept connections

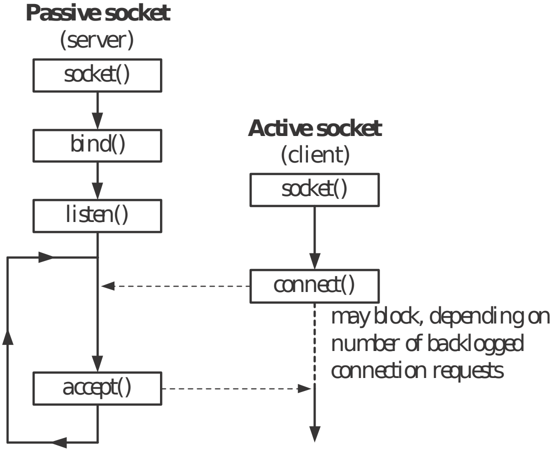
`listen` turns an active socket into a passive one, allowing him to accept incoming connections (i.e. performing passive opens):

```
#include <sys/socket.h>

int listen(int sockfd, int backlog);
```

Returns: *0 on success, -1 on error*

- `sockfd` references the socket we want to affect
- `backlog` specifies the maximum number of pending connections that the passive socket will keep

Pending connections



TLPI, Fig. 56-2

- active opens may be performed before the matching passive ones
- not yet accept-ed connections are called pending
- they may increase or decrease over time, depending on the serving time
- with pending < backlog, connect succeeds immediately
- with pending >= backlog, connect blocks waiting for an accept

Accepting connections

You can accept connections (i.e. perform a passive open) with:

```
#include <sys/socket.h>

int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen);
```

Returns: *file descriptor on success, -1 on error*

If the corresponding active open hasn't been performed yet, accept blocks waiting for it. When the active open happens—or if it has already happened—accept returns a *new* socket connected to the peer socket. The original socket remains available and can be used to accept other connections.

`addr/addrlen` are value-result arguments which will be filled with the address of the peer socket. Pass NULL if not interested

- note: differently from other IPC mechanisms, we might know "who" is our peer

Connecting

To close the puzzle, you connect (i.e. perform an active open) with:

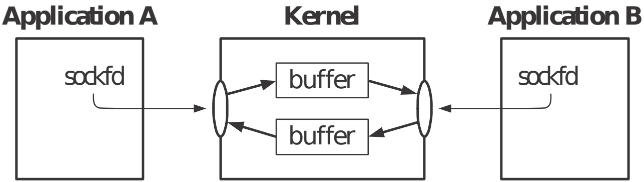
```
#include <sys/socket.h>

int connect(int sockfd, struct sockaddr *addr, socklen_t addrlen);
```

Returns: *0 on success, -1 on error*

- `sockfd` is *your own* socket, to be used as your endpoint of the connection
- `addr`/`addrlen` specify the well-known address of the peer you want to connect to, and are given in the same format of `bind` parameters

Communicating via stream sockets

Once a connection between two peer socket is established, communication happens via `read`/`write` on the corresponding file descriptors:



TLPI, Fig. 56-3

`close` on one end will have the same effects of closing one end of a pipe:

- reading from the other end will return EOF
- writing to the other end will fail with EPIPE error and send SIGPIPE to the writing process

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Socket addresses in the UNIX domain

We now want to give an example of stream sockets. To do so, we can longer remain in the abstract of general sockets, but we need to pick a domain. We pick the UNIX domain.

In the UNIX domain, addresses are pathnames. The corresponding C structure is sockaddr_un:

```
struct sockaddr_un {
    sa_family_t sun_family;     /* = AF_UNIX */
    char        sun_path[108];  /* socket pathname,
                                   NULL-terminated */
}
```

The field sun_path contains a regular pathname, pointing to a special file of type socket (≠ pipe) which will be created at bind time.

During communication the file will have no content, it is used only as a *rendez-vous* point between processes.

Binding UNIX domain sockets — example

```
const char *SOCK_PATH = "/tmp/srv_socket";
int srv_fd;
struct sockaddr_un addr;

srv_fd = socket(AF_UNIX, SOCK_STREAM, 0);
if (srv_fd < 0)
        err_sys("socket error");

memset(&addr, 0, sizeof(struct sockaddr_un));
  /* ensure that all fields, including non-standard ones,
     are initialized to 0 */
addr.sun_family = AF_UNIX;
strncpy(addr.sun_path, SOCK_PATH, sizeof(addr.sun_path) - 1);
  /* we copy one byte less, ensuring a trailing 0 exists */

if (bind(srv_fd, (struct sockaddr *) &addr,
            sizeof(struct sockaddr_un)) < 0)
        err_sys("bind error");
```

Binding UNIX domain socket — caveats

- the actual filesystem entry is created at bind time
  - if the file already exists, bind will fail
  - it's up to you to remove stale sockets as needed
- ownership/permissions on the file are determined as usual (effective user id, umask, etc.)
  - to connect to a socket you need write permission on the corresponding file
- stat().st_mode == S_IFSOCK and ls shows:

```
/var/run/systemd$ ls -lF shutdownd
srw------- 1 root root 0 dic  9 19:34 shutdownd=
```

- you can't open() a UNIX domain socket, you must connect() to it

Client-server stream socket — example

To experiment with stream sockets in the UNIX domain we will write a client-server echo application where:

- the client connects to the server and transfers its entire standard input to it
- the server accepts a connection, and transfers all the data coming from it to standard output
- the server is iterative: it processes one connection at a time, reading all of its data (potentially infinite) before processing other connections

Client-server stream socket example — protocol

```
#include <sys/un.h>
#include <sys/socket.h>
#include <unistd.h>
#include "helpers.h"

#define SRV_SOCK_PATH    "/tmp/ux_socket"

#define BUFFSIZE         1024

#define SRV_BACKLOG      100

/* end of stream-proto.h */
```

Client-server stream socket example — server

```
#include "stream-proto.h"

int main(int argc, char **argv) {
        struct sockaddr_un addr;
        int srv_fd, cli_fd;
        ssize_t bytes;
        char buf[BUFFSIZE];

        if ((srv_fd = socket(AF_UNIX, SOCK_STREAM, 0)) < 0)
                err_sys("socket error");

        memset(&addr, 0, sizeof(struct sockaddr_un));
        addr.sun_family = AF_UNIX;
        strncpy(addr.sun_path, SRV_SOCK_PATH,
                sizeof(addr.sun_path) - 1);
        if (access(addr.sun_path, F_OK) == 0)
                unlink(addr.sun_path);
        if (bind(srv_fd, (struct sockaddr *) &addr,
                 sizeof(struct sockaddr_un)) < 0)
                err_sys("bind error");
```

Client-server stream socket example — server (cont.)

```
    if (listen(srv_fd, SRV_BACKLOG) < 0)
        err_sys("listen error");

    for (;;) {
        if ((cli_fd = accept(srv_fd, NULL, NULL)) < 0)
            err_sys("accept error");

        while ((bytes = read(cli_fd, buf, BUFFSIZE)) > 0)
            if (write(STDOUT_FILENO, buf, bytes) != bytes)
                err_sys("write error");
        if (bytes < 0)
            err_sys("read error");

        if (close(cli_fd) < 0)
            err_sys("close error");
    }
}
/* end of stream-server.c */
```

Client-server stream socket example — client

```c
#include "stream-proto.h"

int main(int argc, char **argv) {
	struct sockaddr_un addr;
	int srv_fd;
	ssize_t bytes;
	char buf[BUFFSIZE];

	if ((srv_fd = socket(AF_UNIX, SOCK_STREAM, 0)) < 0)
		err_sys("socket error");

	memset(&addr, 0, sizeof(struct sockaddr_un));
	addr.sun_family = AF_UNIX;
	strncpy(addr.sun_path, SRV_SOCK_PATH,
		sizeof(addr.sun_path) - 1);
	if (connect(srv_fd, (struct sockaddr *) &addr,
		 sizeof(struct sockaddr_un)) < 0)
		err_sys("connect error");
```

```
    while ((bytes = read(STDIN_FILENO, buf, BUFFSIZE)) > 0)
        if (write(srv_fd, buf, bytes) != bytes)
            err_sys("write error");
    if (bytes < 0)
        err_sys("read error");

    exit(EXIT_SUCCESS);
}
/* end of stream-client.c */
```

Client-server stream socket example

Demo

Notes:

- the server accepts multiple connections, iteratively
- we can't directly open its socket (e.g. using shell redirections)

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The mail analogy for datagram sockets

Datagram socket / mail analogy

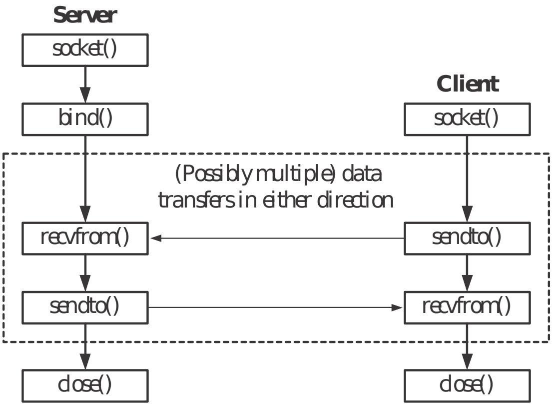
To communicate applications send (snail) mail messages to their peer mailboxes.

- both: `socket()` → installing a mailbox
- both:[4] `bind()` → get a postal address
- peer A: `sendto()` → send a letter to peer B, writing to her postal address
- peer B: `recvfrom()` → check mailbox to see if a letter has arrived, waiting for it if it's not the case
  - each letter is marked with the sender address, so peer B can write back to peer A even if her address is not public

As it happens with the postal system letters can be reordered during delivery and might not arrive. Additionally, with datagram sockets "letters" can be duplicated.

[4] whether you need `bind` to *receive* messages depends on the domain

Datagram socket syscalls — overview



TLPI, Fig. 56-2

Sending datagrams

The sendto syscall is used to send a single datagram to a peer:

```
#include <sys/socket.h>

ssize_t sendto(int sockfd, void *buffer, size_t length, int flags,
               const struct sockaddr *dest_addr, socklen_t addrlen);
```

Returns: *bytes sent on success, -1 on error*

- the return value and the first 3 arguments are as in `write`
- `flags` can be specified to request socket-specific features
- `dest_addr/addrlen` specify the destination address

Receiving datagrams

The `recvfrom` is used to receive a single datagram from a peer:

```
#include <sys/socket.h>

ssize_t recvfrom(int sockfd, void *buffer, size_t length, int flags,
                 struct sockaddr *src_addr, socklen_t *addrlen);
```

Returns: *bytes received on success, 0 on EOF, -1 on error*

- the return value and the first 3 arguments are as in `read`
  - note: `recvfrom` always fetch exactly 1 datagram, regardless of `length`; if `length` it's too short the message will be truncated
- `flags` are as in `sendto`
- `dest_addr/addrlen` are value-result arguments that will be filled with the sender address; specify NULL if not interested

If no datagram is available yet, `recvfrom` blocks waiting for one.

UNIX domain datagram sockets

Whereas *in general* datagram sockets are not reliable, datagram sockets in the UNIX domain are reliable: all messages are either delivered or reported as missing to the sender, non-reordered, non-duplicated.

To be able to receive datagrams (e.g. replies from a server), you should name client sockets using `bind`.

To be able to send datagrams you need write permission on the corresponding file.

On Linux you can send quite large datagrams (e.g. 200 KB, see `/proc/sys/net/core/wmem_default` and the `socket(7)` manpage). On other UNIX you find limits as low as 2048 bytes.

Client-server datagram socket — example

To experiment with datagram sockets in the UNIX domain we will write a client/server application where:

- the client takes a number of arguments on its command line and send them to the server using separate datagrams
- for each datagram received, the server converts it to uppercase and send it back to the client
- the client prints server replies to standard output

For this to work we will need to `bind` all involved sockets to pathnames.

Client-server datagram socket example — protocol

```c
#include <ctype.h>
#include <sys/un.h>
#include <sys/socket.h>
#include <unistd.h>
#include "helpers.h"


#define SRV_SOCK_PATH    "/tmp/uc_srv_socket"
#define CLI_SOCK_PATH    "/tmp/uc_cli_socket.%ld"

#define MSG_LEN          10

/* end of uc-proto.h, based on TLPI Listing 57-5,
   Copyright (C) Michael Kerrisk, 2010. License: GNU AGPL-3+ */
```

Client-server datagram socket example — server

```
#include "uc-proto.h"

int main(int argc, char *argv[]) {
	struct sockaddr_un srv_addr, cli_addr;
	int srv_fd, i;
	ssize_t bytes;
	socklen_t len;
	char buf[MSG_LEN];

	if ((srv_fd = socket(AF_UNIX, SOCK_DGRAM, 0)) < 0)
		err_sys("socket error");

	memset(&srv_addr, 0, sizeof(struct sockaddr_un));
	srv_addr.sun_family = AF_UNIX;
	strncpy(srv_addr.sun_path, SRV_SOCK_PATH,
		sizeof(srv_addr.sun_path) - 1);
	if (access(srv_addr.sun_path, F_OK) == 0)
		unlink(srv_addr.sun_path);
	if (bind(srv_fd, (struct sockaddr *) &srv_addr,
		 sizeof(struct sockaddr_un)) < 0)
		err_sys("bind error");
```

Client-server d.gram socket example — server (cont.)

```
    for (;;) {
        len = sizeof(struct sockaddr_un);
        if ((bytes = recvfrom(srv_fd, buf, MSG_LEN, 0,
                        (struct sockaddr *) &cli_addr, &len)) < 1)
            err_sys("recvfrom error");
        printf("server received %ld bytes from %s\n",
                (long) bytes, cli_addr.sun_path);
        for (i = 0; i < bytes; i++)
            buf[i] = toupper((unsigned char) buf[i]);
        if (sendto(srv_fd, buf, bytes, 0,
                (struct sockaddr *) &cli_addr, len) != bytes)
            err_sys("sendto error");
    }
}
/* end of uc-server.c, based on TLPI Listing 57-6,
   Copyright (C) Michael Kerrisk, 2010. License: GNU AGPL-3+ */
```

Client-server datagram socket example — client

```
#include "uc-proto.h"

int main(int argc, char *argv[]) {
        struct sockaddr_un srv_addr, cli_addr;
        int srv_fd, i;
        size_t len;
        ssize_t bytes;
        char resp[MSG_LEN];

        if (argc < 2)
                err_quit("Usage: uc-client MSG...");

        if ((srv_fd = socket(AF_UNIX, SOCK_DGRAM, 0)) < 0)
                err_sys("socket error");
        memset(&cli_addr, 0, sizeof(struct sockaddr_un));
        cli_addr.sun_family = AF_UNIX;
        snprintf(cli_addr.sun_path, sizeof(cli_addr.sun_path),
                 CLI_SOCK_PATH, (long) getpid());
        if (bind(srv_fd, (struct sockaddr *) &cli_addr,
                 sizeof(struct sockaddr_un)) == -1)
                err_sys("bind error");
```

Client-server d.gram socket example — client (cont.)

```
	memset(&srv_addr, 0, sizeof(struct sockaddr_un));
	srv_addr.sun_family = AF_UNIX;
	strncpy(srv_addr.sun_path, SRV_SOCK_PATH,
		sizeof(srv_addr.sun_path) - 1);
	for (i = 1; i < argc; i++) {
		len = strlen(argv[i]);

		if (sendto(srv_fd, argv[i], len, 0,
			   (struct sockaddr *) &srv_addr,
			   sizeof(struct sockaddr_un)) != len)
			err_sys("sendto error");
		if ((bytes = recvfrom(srv_fd, resp, MSG_LEN,
				      0, NULL, NULL)) < 0)
			err_sys("recvfrom error");
		printf("response %d: %.*s\n", i, (int) bytes, resp);
	}
	unlink(cli_addr.sun_path);
	exit(EXIT_SUCCESS);
}
/* end of uc-client.c, based on TLPI Listing 57-7,
   Copyright (C) Michael Kerrisk, 2010. License: GNU AGPL-3+ */
```

Demo

Notes:

- the server is persistent and processes one datagram at a time, no matter the client process, i.e. there is no notion of connection
- messages larger than 10 bytes are silently truncated