Building Applications out of Several Programs

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Overview of Course

Mainly the principles of whys, whens and hows

Start with elementary overview
Then describe chains
And other basic structures
How to design and code interfaces

More advanced topics (optional)
Problems with monolithic programs
Some issues with separate programs
And more advanced structures

Beyond the Course

http://docs.python.org and/or books on it
Go to Python courses if you don't know it

http://www.perl.org/docs.html and/or books on it
E.g. Programming Perl, Third Edition, O'Reilly Media
by Larry Wall, Tom Christiansen and Jon Orwant

Email scientific–computing@ucs for advice
Could arrange further courses

Using Separate Programs

Will give the most common reasons
But there are many, many others

Golden rules:

- KISS – Keep It Simple and Stupid
- Only divide up in 'natural' ways
- Use a simple, debuggable structure
- Interfaces are AS important as components

Basic Controller Model

- Controller ($\equiv$ harness) does very little
Controls how programs start and communicate
Handles program failure (return code or crash)

- Programs run in isolation from each other
No communication except as set up by the controller
Components can be existing, free–standing programs
They do all of the real work

- Not the only model – just the simplest

Using Existing Programs

May want a different sort of interface
Simpler/clearer/area–specific/flexible/GUI
May need to automate some analyses

May need to combine several programs
Possibly in binary, different languages etc.
Avoids mixed–language executable problems

This is just industrial–strength scripting

- $\equiv$ programming using processes

Splitting Up Programs

- Can often increase debuggability

Provides interfaces to locate bugs/problems
Can often debug components separately
Can use to avoid library incompatibilities

- Sometimes critical for efficiency:

Run in parallel on multi–core systems
Can even use some components remotely
GUI code will ‘poison’ HPC (SMP or not)

Choice of Languages

- Components can be written in anything
Process interface is language–independent
Binaries are usually in no known language!
And, yes, each program can be different

Controlling programs: Python, Perl etc.
C++, Fortran 90 etc. are OK but more effort
Complex shell scripting is for masochists

- Python is the recommended tool

Advanced Controllers

Iris Explorer (from NAG)
Data Explorer (ex–IBM)
Many others used in commerce

Mostly GUI–based, hard to learn
A few users in the University
Worthwhile for very heavyweight tasks

Some job schedulers fall into this category

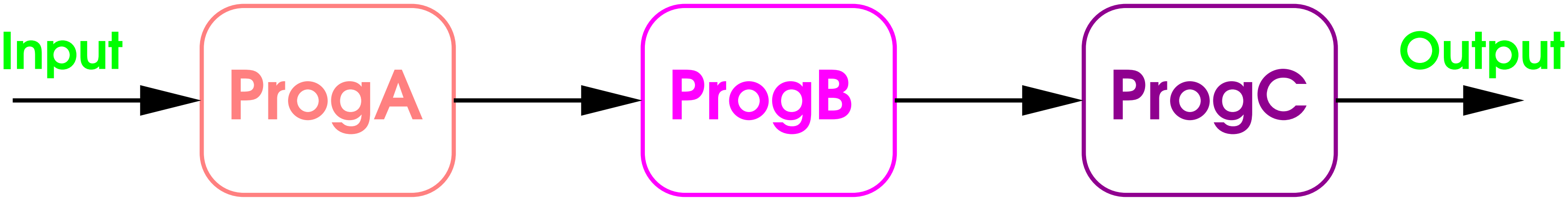
Basic Structures

Some structures are easy to use/debug
Can even prove mathematically correct
90% of applications can use one of them
99% can use a clean combination

Will mention places where problems occur
But mainly to say "don't go there"

Remember, one golden rule is about these

Simple Chains



ProgB must wait for ProgA

ProgC must wait for ProgB

Data/control flow is from input to output

Basic Simplex Chains

A.k.a. pipes, streams, FIFOs, queues, sockets
Serial from single input to single output
Can use large buffers and many CPUs/systems
Streaming I/O can be optimally efficient

Control and data flow are simply linear
Done automatically by shell pipelines
Very simple, very reliable, easy to test

Will return to interactive chains later

Controlling Chains

- The shell creates a pipe (with two ends!)
- Starts program A and feeds output into pipe
- Starts program B taking its input from pipe

But does NOT handle errors correctly!

Controlling programs should do the same
No other synchronisation needed or wanted
But should also detect errors . . .

Using default I/O almost always OK

Python Chain Controller

huey | dewey | louie

```
from sys import stdin, stdout
from subprocess import Popen, PIPE
p1 = Popen(["huey"],stdout=PIPE)
p2 = Popen(["dewey"],stdin=p1.stdout, \
      stdout=PIPE)
p3 = Popen(["louie"],stdin=p2.stdout)
rc = p3.wait()
```

Python Error Handling

- Wait for or kill all subprocesses
- Print subprocess name and error code
- Possibly trap exception OSError

See example in Python library manual
Only 8 not–very–complex lines

Check return codes from all subprocesses

Best programs check have reached EOF on input
And get EOF when all output has been read

Python Error Code

```
try:
    rc = call(cmd+args, shell=True)
    if rc < 0:
        print >>sys.stderr, cmd+" sig", –rc
    else:
        print >>sys.stderr, cmd+" exit", rc
except OSError, e:
    print >>sys.stderr, cmd+" fail:", e
```

Perl Chain Controller

See “Programming Perl”, chapter 16

Some very simple cases are easy
In general, not much easier than C
Very little error handling by default

Remember to clean up environment

- Not advised unless you know Perl already

C/C++/POSIX Controller

Too complicated for this course

- Avoid this if you possibly can

Need pipe()/dup2()/fork()/exec?()/waitpid()

Plus cleaning up programming environment

Not doing so can cause confusion/chaos

Example code is shown later

And that's just for the simple case!

Fortran Controller

Calls C to do actual process control
Advanced logic can be in Fortran

Not worthwhile for simple chain control
Starts being so for master/worker

Please ask for help if doing this

Python Component

This is what ‘cat’ looks like:

```
from sys import stdin, stdout
while 1 :
    line = stdin.readline()
    if not line :
        break
    stdout.write(line)
```

Or Perl?

```
while (<STDIN>) {
    print $_;
}
```

But you will need to add error handling!
Perl includes very little automatically

Or Fortran?

```
character, len=big_enough :: buffer
do
    read (*,'(a)',end=10) buffer
    write (*,'(a)') buffer
enddo
10 continue
```

Fortran errors default to fatal, as in Python

Or C++? Or C?

```
string s;
while (cin >> s) cout << s << std::endl;
```

```
char buffer[big_enough];
while (fgets(buffer,sizeof(buffer)–1,stdin) {
    buffer[sizeof(buffer)–1] = '0';
    fputs(buffer,stdin);
}
```

Remember about error handling here, too

Golden Rules of I/O

- Use streaming I/O – allow reblocking
- Don't reposition/handshake in any way

- For performance use binary/unformatted

Use large buffers (64+ KB) if possible

- Check but distrust all error codes

Close explicitly and check return code

Another Method

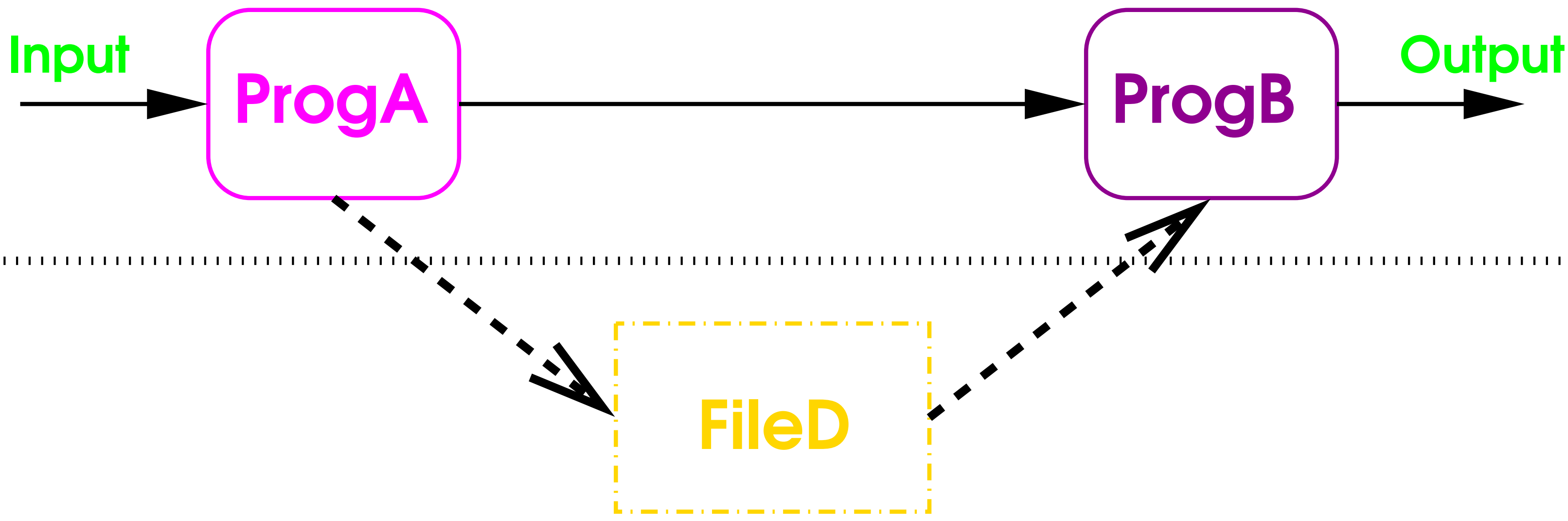
Program A spawns program B (i.e. fork+exec)
Program A waits for program B to finish
First orders start of B, second orders end of B

Or controlling program runs A, and then B

Can also send messages down pipe
Or by using signals (not recommended)

This logic is needed if using files for data
Must close output before opening for input

Using Files in Chains



ProgA: write & close FileD THEN prod ProgB

ProgB: wait for ProgA THEN open FileD

Python Example (1)

```
from subprocess import Popen
rc1 = Popen(["A"]).wait()
rc2 = Popen(["B"]).wait()
```

Program A:

```
output = open("fred","w")
output.write(some_data)
output.close()
```

Program B:

```
input = open("fred","r")
. . .
```

Python Example (2)

Program A:

```
output = open(filename,''w'')
output.write(some_data)
output.close()
p1 = Popen([''B''])
p1.wait()
```

Program B:

```
input = open(filename,''r'')
. . .
```

Python Example (3)

Program A:

```
output.write(some_data)
output.close()
stdout.write(filename)
```

Program B:

```
name = stdin.readline()
input = open(name)
. . .
```

GUIs - X and MS Windows

Most common requirement for splitting programs

Mandatory event loop with no long delays
Does horrible things with networking
Often demands specific compiler options
Name clashes and other problems abound

Foul to debug – repeatability? evidence?
May even lock up console and force reboot
Solution: separate off and Keep It Simple

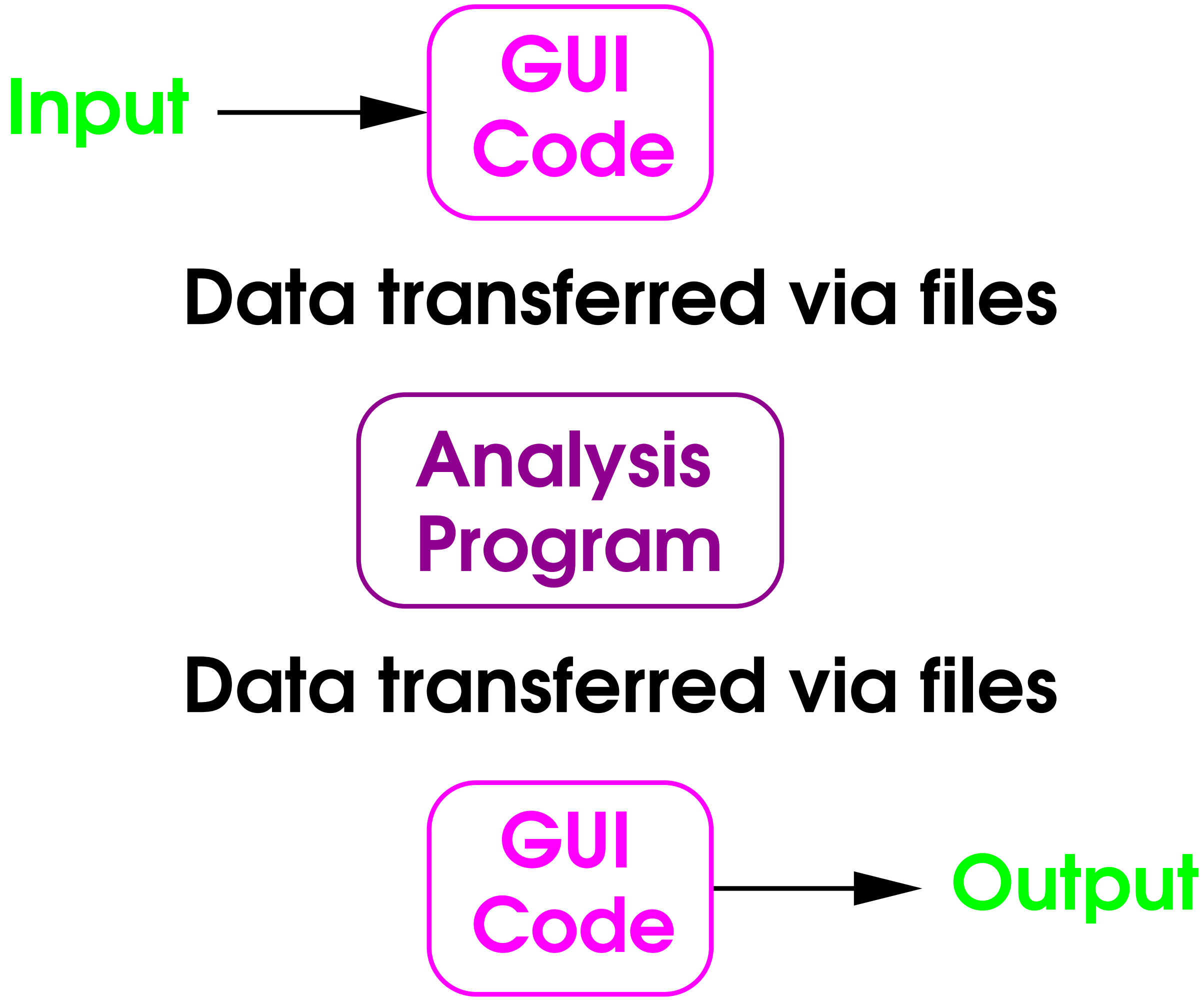
GUI Input and Output

- GUI component creates/checks input files
- Analysis program runs non–interactively
- GUI component displays/selects results

Many commercial/production programs do this
Almost universal in HPC environments
4 decades of experience supports this design

It can save a LOT of debugging time!

Simple GUI Design



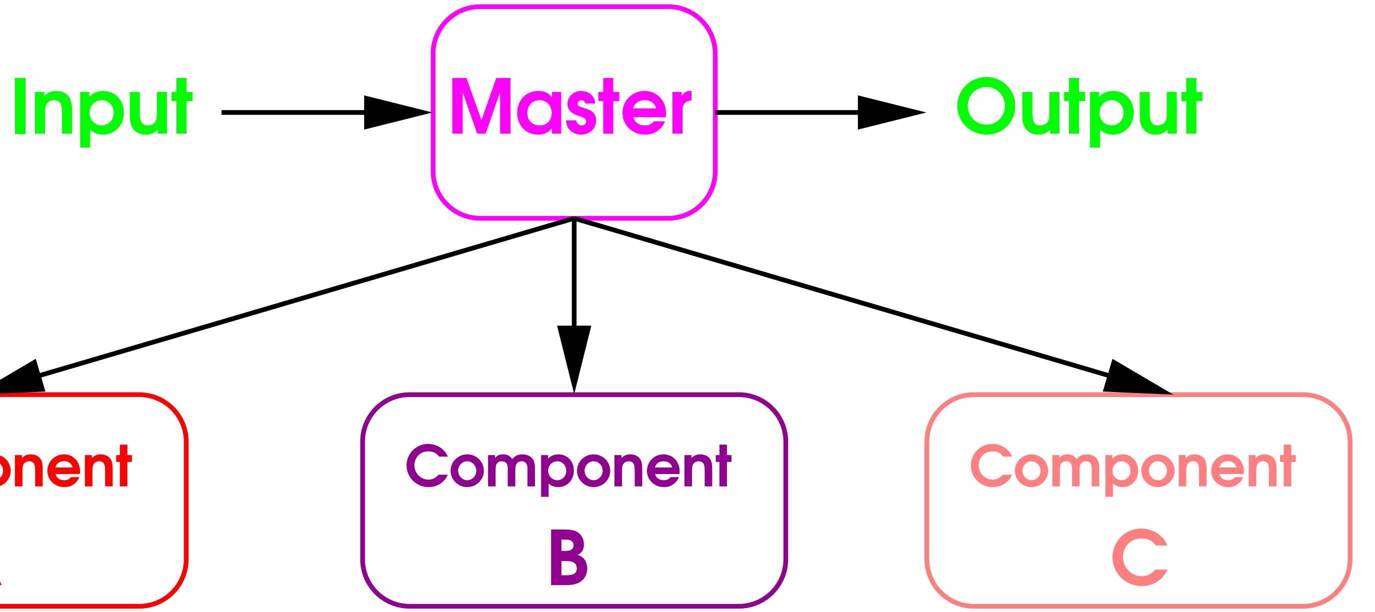
Why Do This?

Can rerun any stage if it fails
Very useful for debugging etc.
Or if you just need to go to bed!

Files provide proof of where errors lie
Can automate (script) creation of input
Or changes, or analysis of output . . .

Analysis may take days or need restarting
Or need to be run on another system

Master/Worker



The master may just do control, or may also do processing (but not in parallel to workers)

Workers may run serially or in parallel

Serial Master/Worker

The master runs the workers serially
Possibly interleaved with its own work
Simple, reliable, but not parallelisable

Spawn and wait for component A
Do some computation in the master
Spawn and wait for component B
Spawn and wait for component C
And so on . . .

Return to the parallel version later

Warnings

Don’t be clever when sharing descriptors
There are some evil ‘gotchas’ lurking

Watch out for environment pollution
Far more of this than most people realise
E.g. signal handling and limits

Tree Structures

Serial master/worker can make a tree
Just function calls to separate programs

Don't expect recursion to work!

Only real problem is handling failures
Killing a process doesn't kill children

More Complex Structures

Key concept is a transaction (coming next)
Effectively an atomic message+reply

Streaming I/O can be used – with care
But remember pipes have finite capacity
Using files for bulk data is much safer

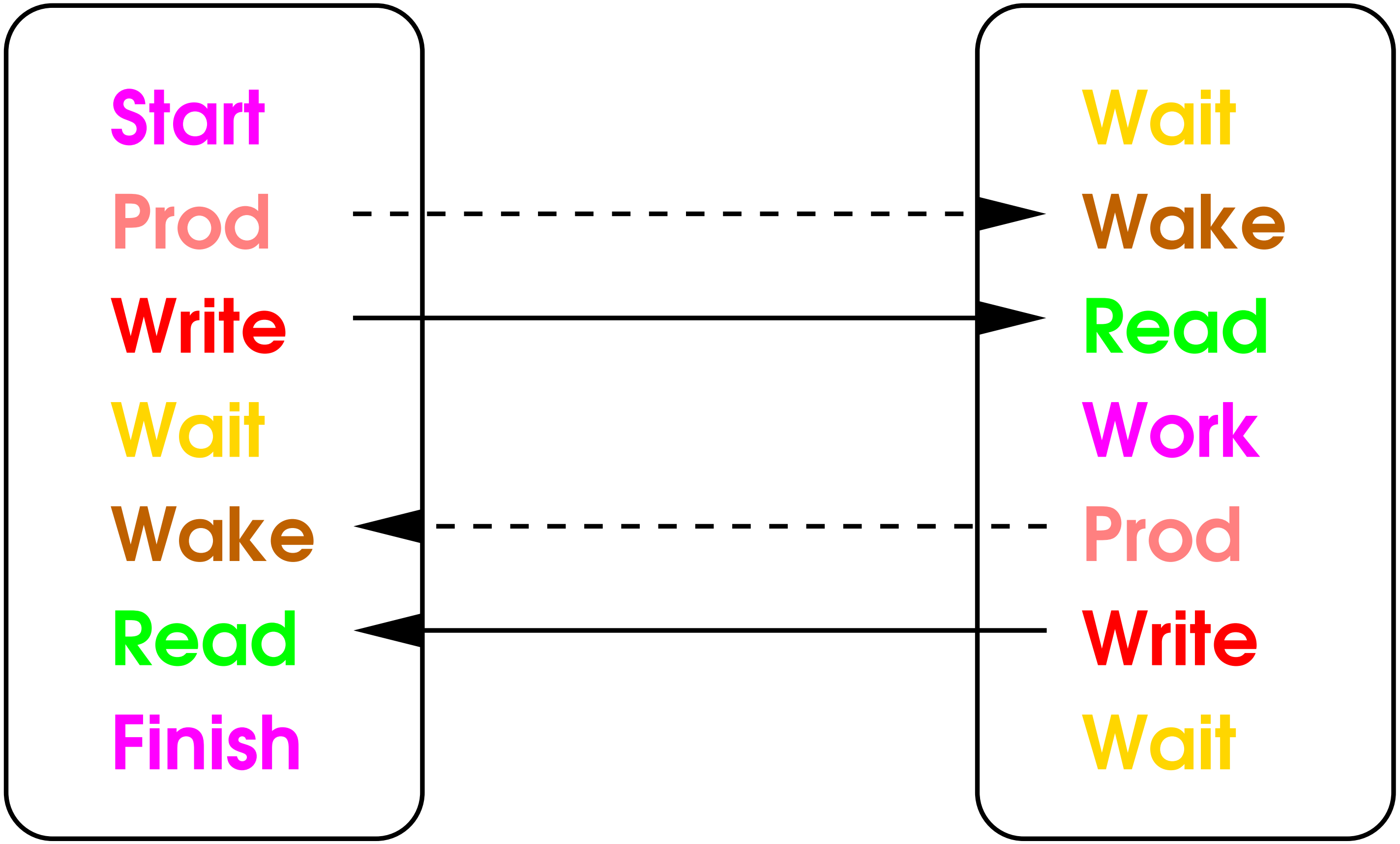
Will give guidelines for safe use
Experts can and do break the rules

Simple Transactions

Program A writes all of its request
Program B reads all of the request
Program B writes all of its reply
Program A reads all of the reply

NO other communication during that
Don’t start reply while reading request
Read reply before sending next request

Transactions



Parallel Master/Worker (1)

The master runs the workers in parallel
Workers talk only to/from their master
Very good for SMP systems and clusters

Read input and divide up work
Spawn all of the workers
Wait for all of the workers
Collect their work
Combine it and write output

Parallel Master/Worker (2)

Master/worker communication can be a problem
Easiest if master supplies input initially
And then just collects results at end
Usually safest when files are used for this

Sometimes ongoing communication is needed
See later on duplex pipes
But avoid it if you possibly can
Use simple transactions if you must do it

Simple Client/Server

The server runs as a daemon (indefinitely)
It waits for requests and responds serially

Clients gather input and send requests
Wait for reply and then produce output
And possibly do this repeatedly

msntp is a very simple example
exim is a more realistic one

Combination Structures

Can combine above structures in many ways
A component can be a combination
But remember to KISS!

Beyond that, really don't go there
Virtually impossible to debug

Some distributed applications do this
Schedulers, desktops, Grid software
Administrators curse them, vigorously

Data Interfaces

Design like external interfaces
You don't make errors? – I do, often
Good way of simplifying debugging

Programs should check input for validity
Checking output can be worthwhile, too
Be thorough, but no need to be paranoid

It really will save you time, overall

Specific Checks

Check formats – bad ones may mean wrapping
Check validity – “NaN” is Not A Number
Check values are in plausible range

Check consistency – e.g. number count
Failures can mean source program crashed
Any check may pick up data corruption

And anything else you can think of

Designing Formats

KISS, and include cross–checks
Include some values just for checking
Counts, maxima, sums, whatever makes sense

Not just N values, but count & N values
Or N values & terminator, or both

```
5    1.2    2.3    3.4    4.5    5.6
1.2    2.3    3.4    4.5    5.6    –1.0e30
5    1.2    2.3    3.4    4.5    5.6    –1.0e30
```

Document It!

A block comment in your code is easy and good
For example:

```
# All main items and rows start on a new line
# Extra spaces and newlines in numbers ignored
#
# Title and author in free text
# Date in format 01/Apr/2006
# Row and column sizes
# Data by row appended with –1.0e30
```

Structured Data

```
Object = < Vector | Matrix >
Vector = Size Newline  \
            Values(Size) Newline
Matrix = Row_size Column_size Newline  \
            Rows(Column_size)
Row = Values(Row_size) Newline
Value = < ’Missing’ | Floating–point >
```

You can spot problems in the format you use
Advantage is your program can decode it
And, with care, can detect and flag errors

You're Now Using BNF!

Read up about BNF (Backus–Naur Form)

Wikipedia is easier than textbooks!

http://en.wikipedia.org/wiki/Backus–Naur_form

It is NOT complex, and very useful
Don't worry about notation – anything goes
You want it mainly to keep your thoughts clear
And to ensure that your code can parse it!

Some Fortrans and C90 didn't and ...

Advanced Topics

Start with problems of monolithic programs
And some that can arise with separate programs

It is worth knowing what the issues are
Mainly to know what examples not to follow
And when to take a different approach

- Beyond here is background information only

I.e. why do the above, and what not to do

Monolithic Program Issues

Can be avoided by using separate programs
Don’t panic over them, but recognise them
Split up if it makes development simpler
But interfaces need design and coding, too!

Don’t mince applications for the sake of it
1970s (and later) computer science dogma
‘Software Tools’, S tend to follow this dogma

KISS and be cautious, and all will be well

Common Incompatibilities

Only a few languages can be linked together
Python, Perl, C++, Fortran 90 must be ‘master’

External name clashes (not easily soluble)
Incompatible use of stdin and stdout
Run–time systems often incompatible
Two garbage collectors is Bad News

Worst is basic paradigm incompatibilities
E.g. are exceptions, longjmp, signals allowed?

HPC, OpenMP etc.

Exactly the converse of GUI requirements
Can dive into libraries for hours
Needs aggressive optimisation and more
Often need special scheduling options

Very often want to run in background
Or even on a remote (and different) system

Solution: create input and ‘run in batch’

‘Interactive’ Chains

Buffered output need not appear until end
In extreme case, not until input is closed
Not a problem for ‘batch’ processing
But very confusing if you aren’t expecting it

Need an end–to–end flush/push – don’t have one
Can ‘solve’ with non–blocking/unbuffered I/O
Details are very messy and system–specific
Avoid if you can – much less efficient

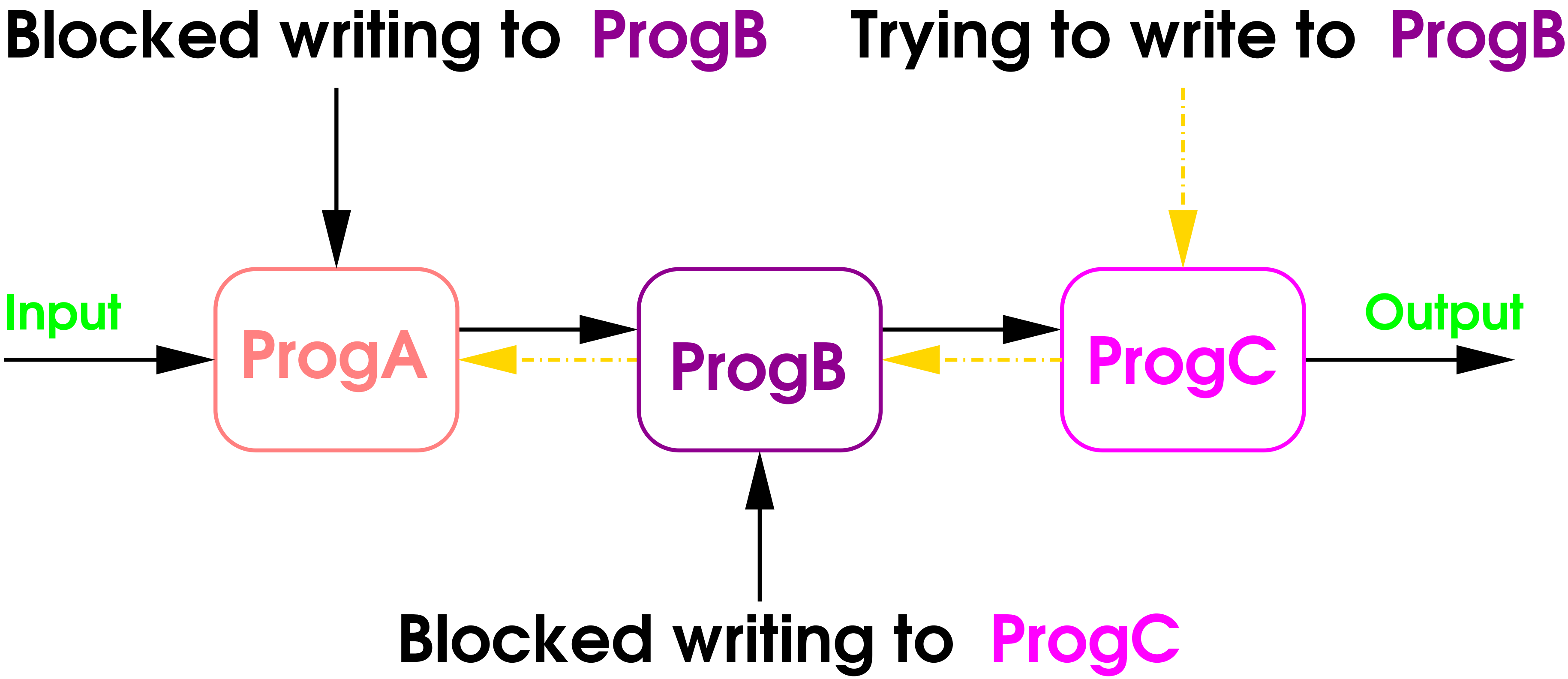
Duplex Pipes

I.e. ones where messages are being sent both ways

Look simple, but aren't (even theoretically)
Seriously misdesigned in POSIX (Microsoft?)
OK if careful – easy to cause deadlock
Don't mix at all well with streaming

Solution:
Communicate using simple transactions only
All messages are short – won't block pipe
Use files if any danger of doing that

Duplex Pipes



If buffers fill up, the application can deadlock!

File Access

Don’t trust consistency guarantees too far

Can read arbitrarily often in parallel
Or update (write) from one component
Be careful when changing between these

Close all uses in all components
Handshake to all components that use file
Only then can safely open file again

File/Pipe/Socket/Memory I/O

Flush/push/fsync unreliable even for local files

Don't trust blocking/non–blocking
POSIX rules are not what they appear
Don't use asynchronous I/O

Shared memory can be very efficient
Treat it like I/O – i.e. handshake
Don't assume consistency by magic

Specific Unix Problems

Some things pass through fork+exec
File descriptors, signal mask,
environment vars, limits . . .

Shells have some hacks to reset them
You may need to do the same
Critical when calling unclean components

Microsoft probably has similar gotchas

Socket/etc. Problems

Sockets are very ‘active’ objects
Any access can affect other uses
Stray open descriptors can delay close
In extreme cases, can hold up output

Can be prone to unexpected temporary hangs
Time–dependent code using them is tricky
Look at code of OpenSSH for examples

Using (Avoiding) Threading

Threads are NOT the solution!
Solve one problem, add half–a–dozen more
Details are beyond scope of this course

Only real use is to avoid blocking problems
Particularly relevant for duplex pipes etc.
Need considerable experience, even so

OpenMP implementations use them – don't ask
Rumours are that some GUI libraries do, too

C/POSIX fork+exec

This is the C code for the chain controller
Complete with tolerable error handling

It is shown mainly to put you off
Please ask for it if you really need it

C Chain Controller (1)

```
/* We start in the parent */
if (pipe(in) != 0 || pipe(out) != 0 ||
        (pid = fork()) < 0) fatal();
```

There are now two processes running this code

C Chain Controller (2)

```
if (pid > 0) {
/* This is in the parent */
        if (close(in[1]) != 0 ||
                close(out[0]) != 0) fatal();
        if (write(out[1],...) < 0 ||
                close(out[1]) != 0) fatal();
        if ((len = read(in[0],...)) < 0 ||
                close(in[0]) != 0) error();

        if (waitpid(pid,&status,0) < 0) fatal();
        if (! WIFEXITED(status) ||
                WEXITSTATUS(status) != 0) error();
```

C Chain Controller (3)

```
} else {
/* This is in the child */
    if (close(in[0]) != 0 || close(out[1]) != 0 ||
            dup2(in[1],STDOUT_FILENO) < 0 ||
            close(in[1]) != 0 ||
            dup2(out[0],STDIN_FILENO) < 0 ||
            close(out[0]) != 0)
        fatal();
    for (i = 0; i <= 63 /* Sigh */; ++i) signal(i,SIG_DFL);
    if ((k = sysconf(_SC_OPEN_MAX)) <= 0) k = 63;
    for (i = 3; i <= k; ++i) close(i);
    execl(spawned_program);
    fatal();
}
```

More Advanced Structures

Don’t go there – really don’t go there
But you already use programs like this
And you may well curse them, vigorously

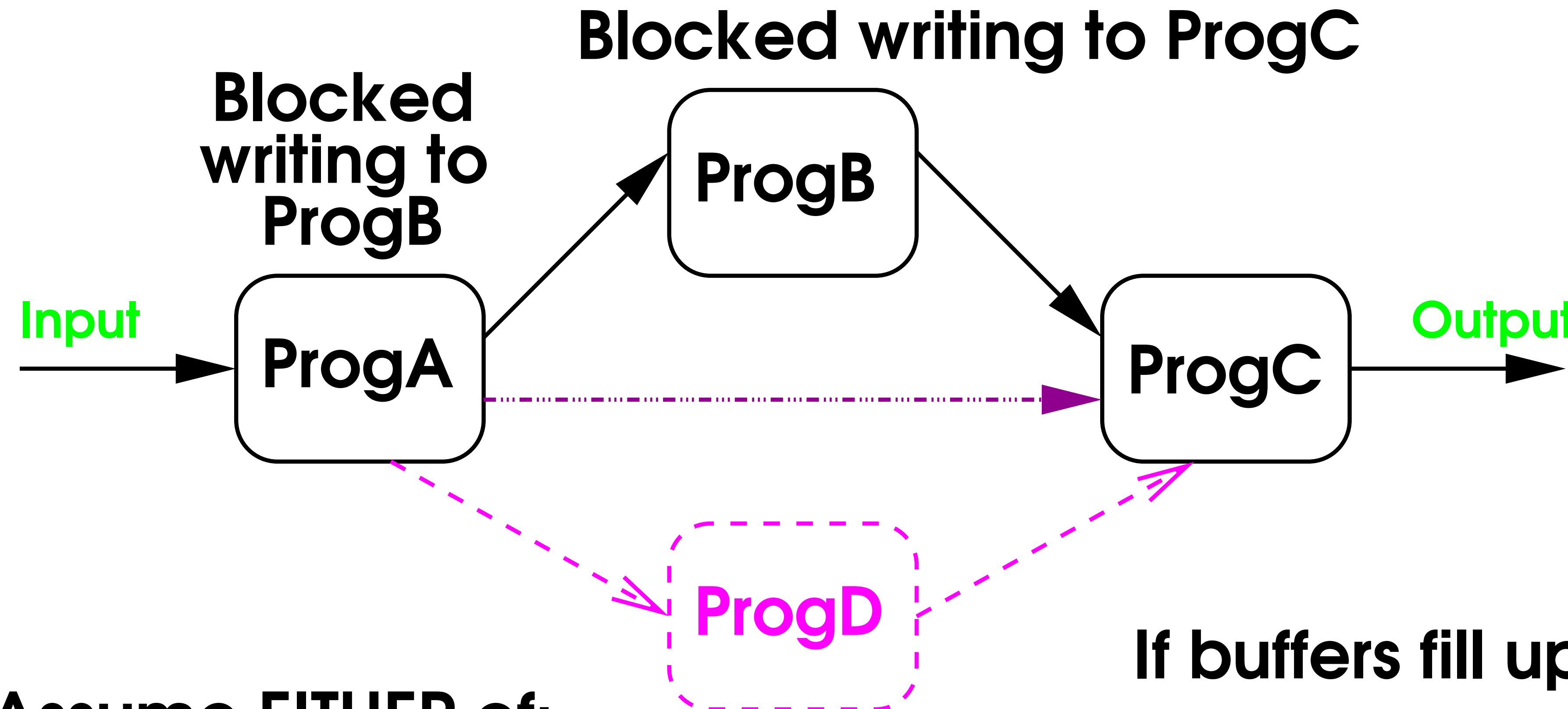
DAGs

Directed acyclic graphs – ones without loops
Can be very useful, but easy to deadlock
Exactly the same problems as duplex pipes

Avoiding deadlock is harder than for duplex
Needs careful design of data/control flow

Very similar problems to interactive I/O

Directed Acyclic Graphs (1)

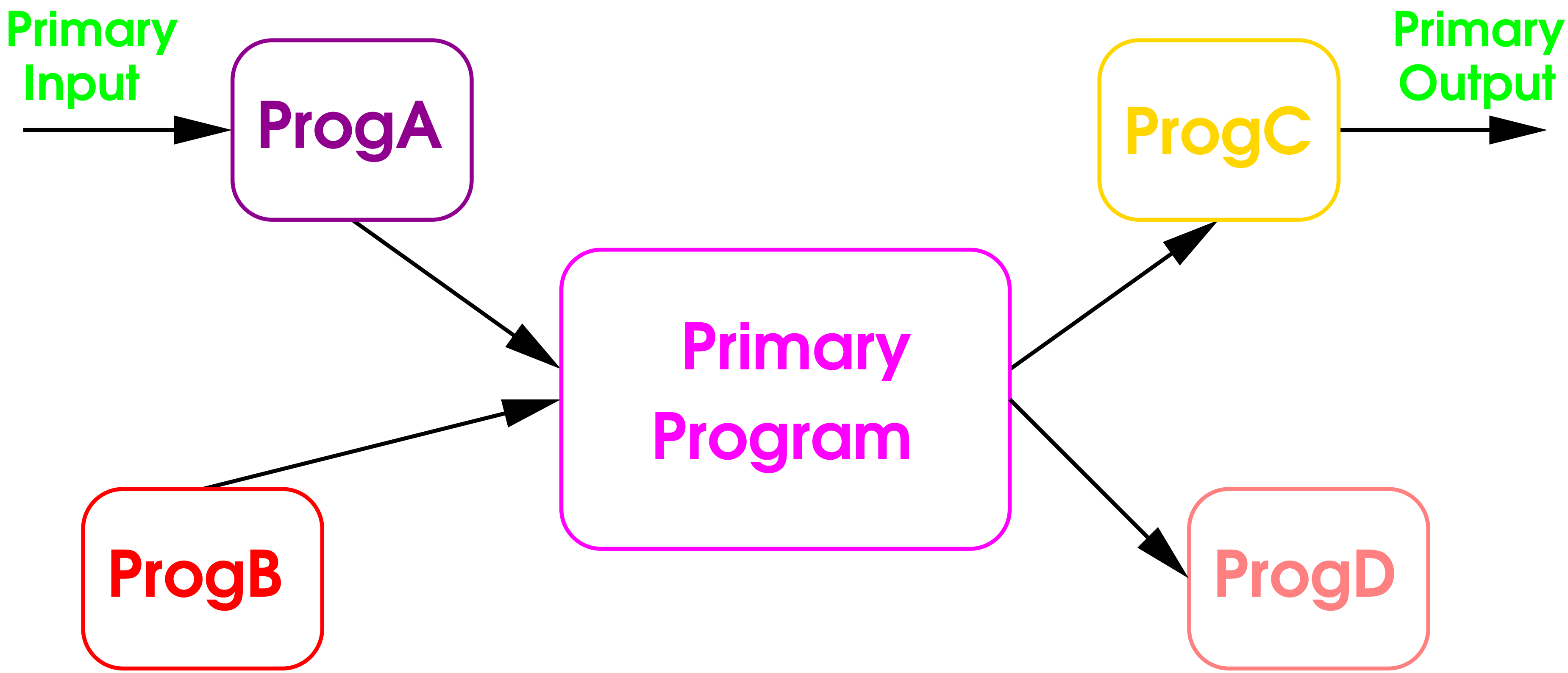


Assume EITHER of:

- ProgC reads from ProgA
- ProgC reads from ProgD

If buffers fill up, the application can deadlock!

Directed Acyclic Graphs (2)



Beyond this gets very confusing, very fast

Multiple Interactive I/O

Use one primary input and one primary output

If two programs reading, which gets the input?
You have NO way of directing input
Use a single input program (GUI?) to control this

Output is generally easier, but still confusing
And output can be merged in the middle of lines!
Causes confusion when piping through grep etc.
Chaos with full–screen (character addressing)

Multiple GUI Components

Theoretically, windows are entirely separate
In practice, this is not quite true

KISS KISS (Keep It SEPARATE, Stupid!)

Focussing, fonts, colours etc. are global
Some programs handshake via X properties

Don't even think of using threading
There can be some EVIL socket issues
$\Rightarrow$ Close all unneeded descriptors

Really Advanced Use

Existing schedulers, desktops, databases etc.
Multiple independent daemons, interacting

Design is a DAG with time–ordering on messages
Need a directed temporarily acyclic graph
Even major vendors don't get those right

Point gun at foot; pull trigger; BANG!