Reproducing Problems

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The First Task

- Once a problem is reported (or exposed by a test), some programmer must fix it.
- The first task is to *reproduce* the problem.

Why reproduce?

- Observing the problem. Without being able to reproduce the problem, one cannot observe it or find any new facts.
- Check for success. How do you know that the problem is actually fixed?

A Tough Problem

- Reproducing is one of the *toughest* problems in debugging.
- One must
  - recreate the *environment* in which the problem occurred
  - recreate the *problem history* – the steps that lead to the problem

Reproducing the Environment

Where to reproduce?	Chances of Success	Costs
User	+	--
Developer	o	+

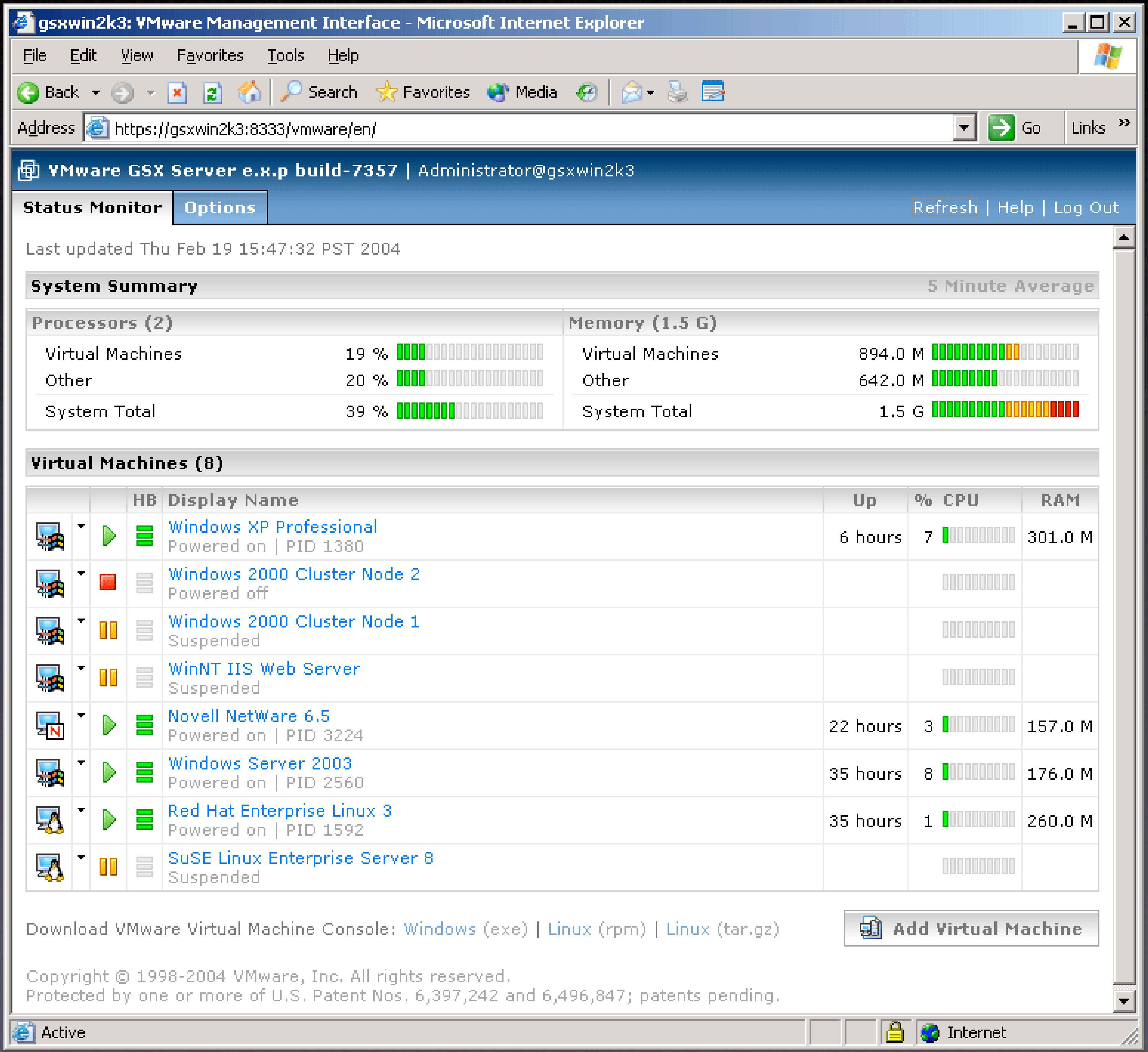
Iterative Reproduction

- Start with *your* environment
- While the problem is not reproduced, adapt more and more circumstances from the *user's* environment
- Iteration ends when problem is reproduced (or when environments are "identical")
- Side effect: Learn about failure-inducing circumstances

Setting up the Environment

- Millions of configurations
- Testing on dozens of different machines
- All needed to find & reproduce problems

Virtual Machines



https://gsxwin2k3:8333/vmware/en/

VMware GSX Server e.x.p build-7357 | Administrator@gsxwin2k3

Last updated Thu Feb 19 15:47:32 PST 2004

System Summary 5 Minute Average

Processors (2)		Memory (1.5 G)	
Virtual Machines	19 %	Virtual Machines	894.0 M
Other	20 %	Other	642.0 M
System Total	39 %	System Total	1.5 G

Virtual Machines (8)

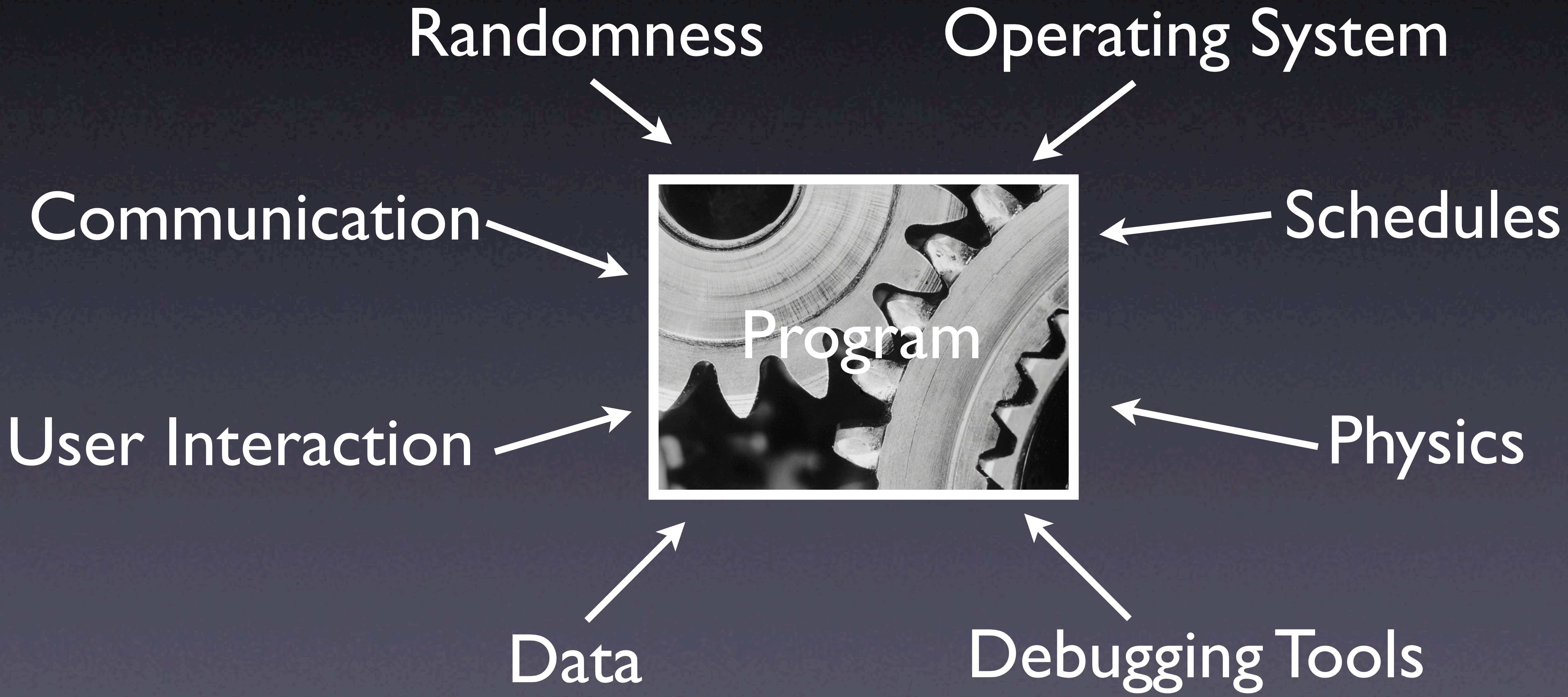
	HB	Display Name	Up	% CPU	RAM
▶	☰	Windows XP Professional Powered on | PID 1380	6 hours	7	301.0 M
■		Windows 2000 Cluster Node 2 Powered off			
❚❚		Windows 2000 Cluster Node 1 Suspended			
❚❚		WinNT IIS Web Server Suspended			
▶	☰	Novell NetWare 6.5 Powered on | PID 3224	22 hours	3	157.0 M
▶	☰	Windows Server 2003 Powered on | PID 2560	35 hours	8	176.0 M
▶	☰	Red Hat Enterprise Linux 3 Powered on | PID 1592	35 hours	1	260.0 M
❚❚		SuSE Linux Enterprise Server 8 Suspended			

Download VMware Virtual Machine Console: Windows (exe) | Linux (rpm) | Linux (tar.gz)

Reproducing Execution

- After reproducing the environment, we must reproduce the *execution*
- Basic idea: Any execution is determined by the *input* (in a general sense)
- Reproducing input → reproducing execution!

Program Inputs



Randomness

Operating System

Communication

Schedules

Program

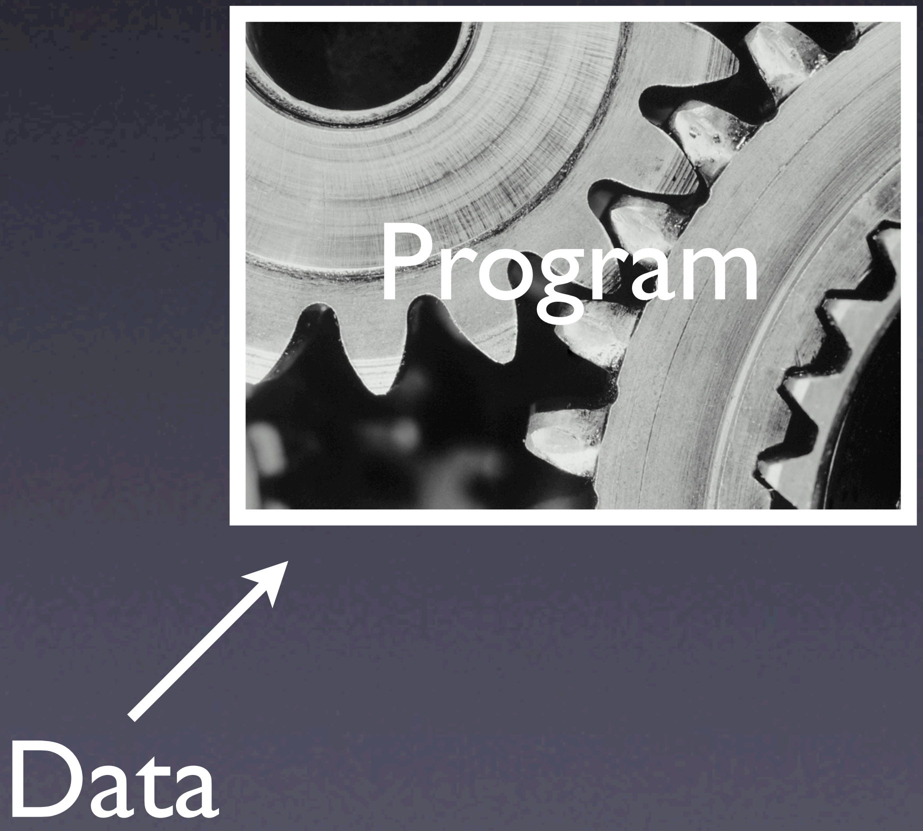
User Interaction

Physics

Data

Debugging Tools

Program Inputs



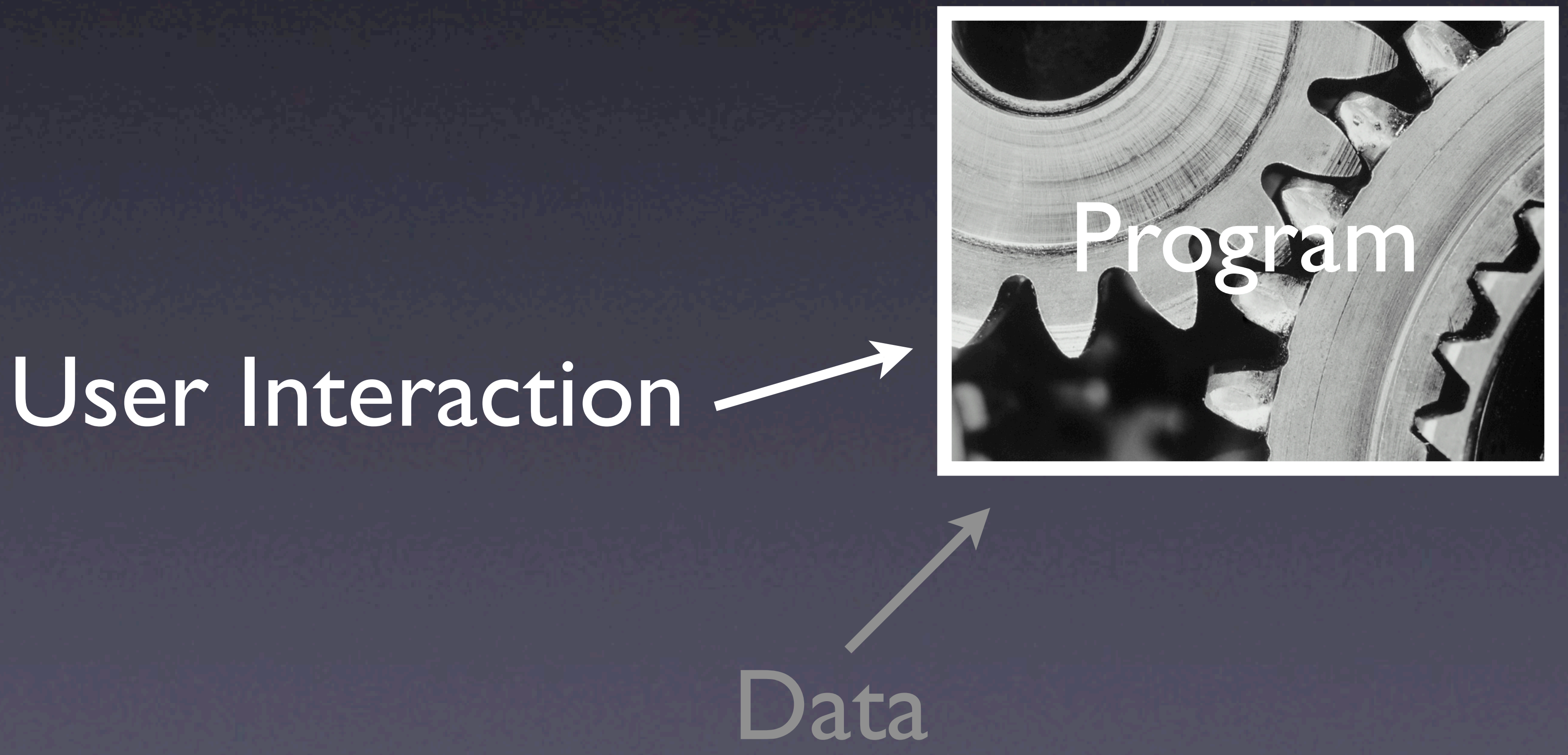
Program

Data

Data

- Easy to transfer and replicate
- Caveat #1: *Get all the data you need*
- Caveat #2: *Ger only the data you need*
- Caveat #3: Privacy issues

Program Inputs

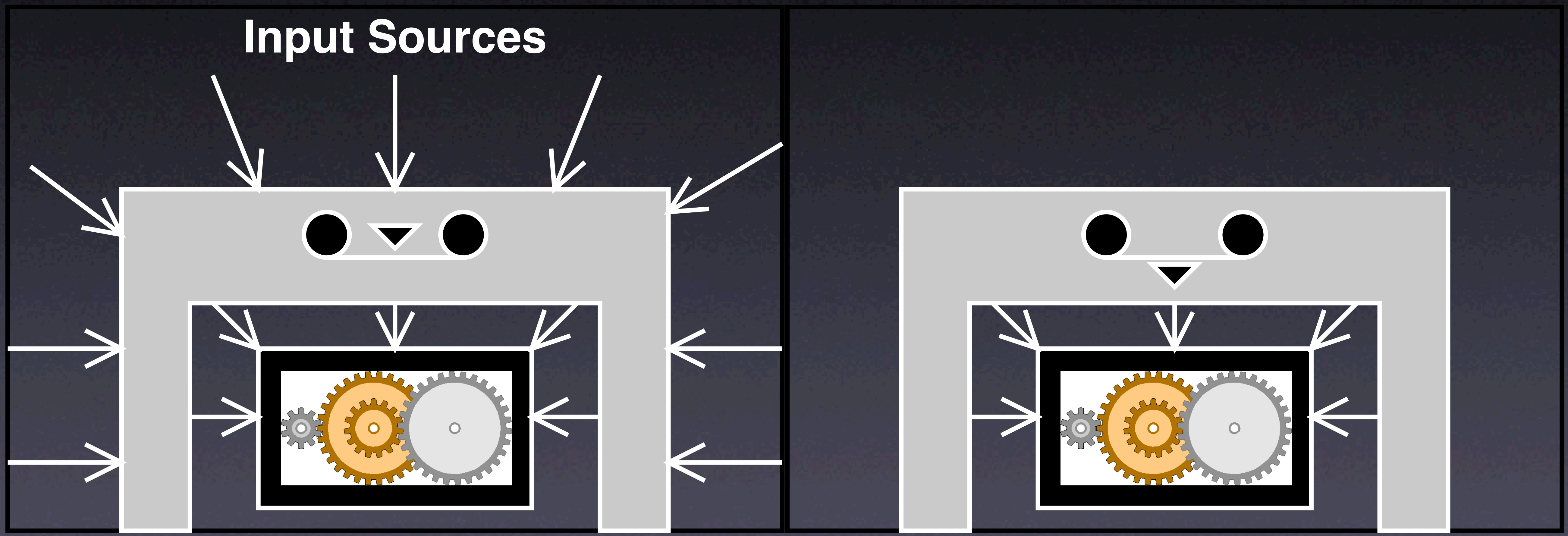


Program

User Interaction

Data

User Interaction



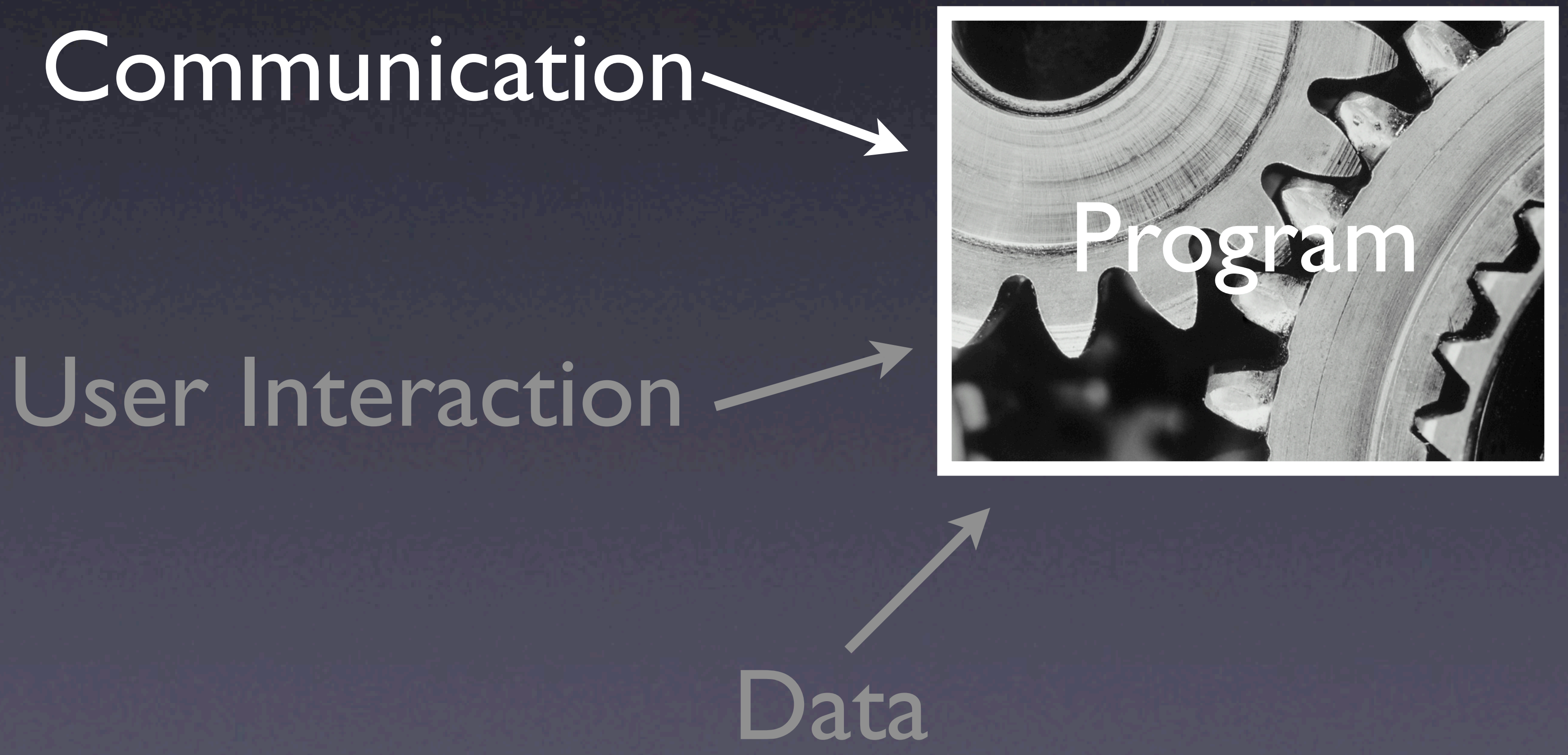
Record

Replay

Recorded Interaction

```
send_xevents key H @400,100
send_xevents wait 376
send_xevents key T @400,100
send_xevents wait 178
send_xevents key T @400,100
send_xevents wait 214
send_xevents key P @400,101
send_xevents wait 537
send_xevents keydn Shift_L @400,101
send_xevents wait 218
send_xevents key “;” @400,101
send_xevents wait 167
send_xevents keyup Shift_L @400,101
send_xevents wait 1556
send_xevents click 1 @428,287
send_xevents wait 3765
```

Program Inputs



Communication

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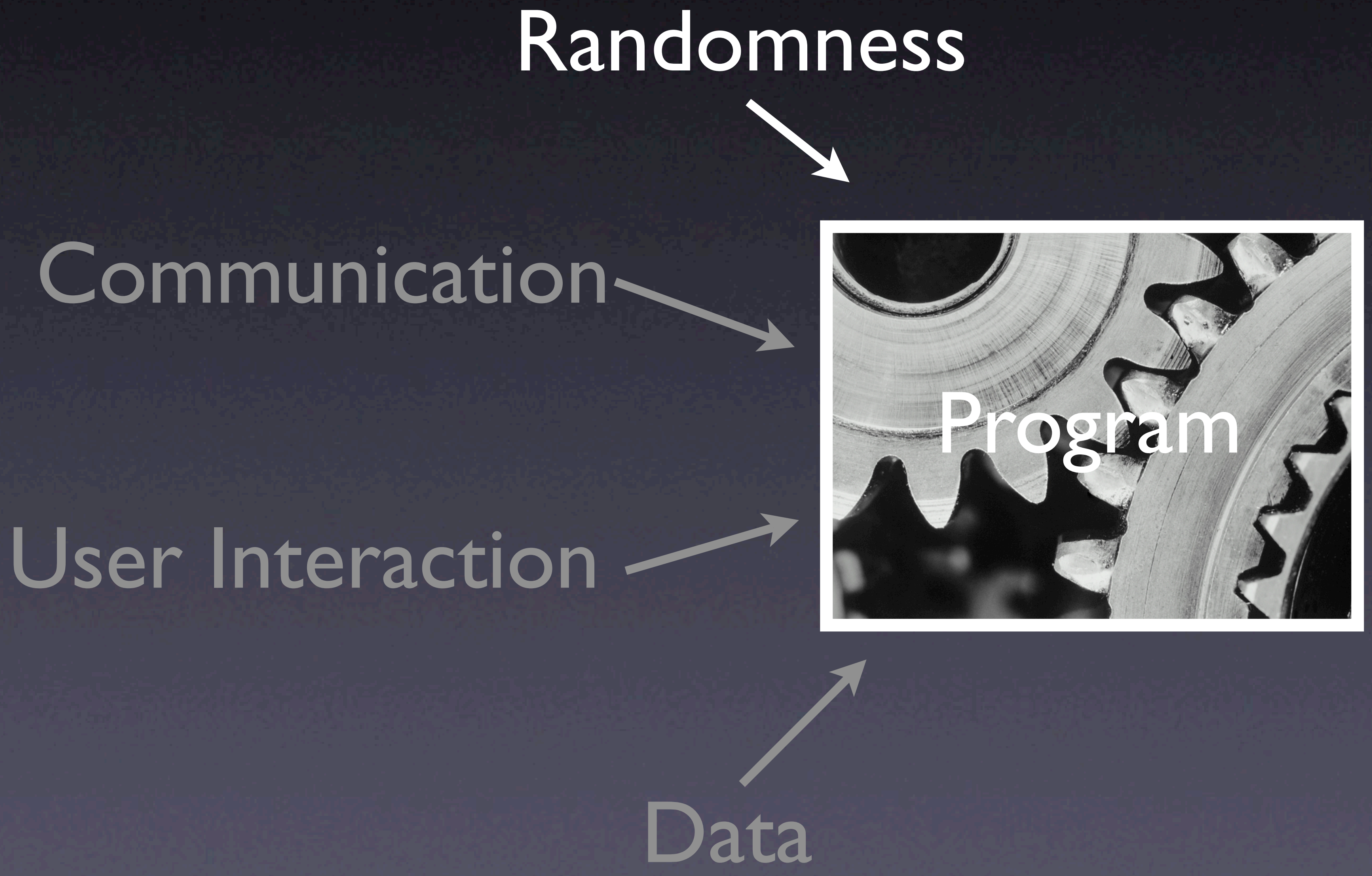
User Interaction

Data

Communication

- General idea: Record and replay like user interaction
- Bad impact on performance
- Alternative #1: Only record since last *checkpoint* (= reproducible state)
- Alternative #2: Only record “last” transaction

Program Inputs



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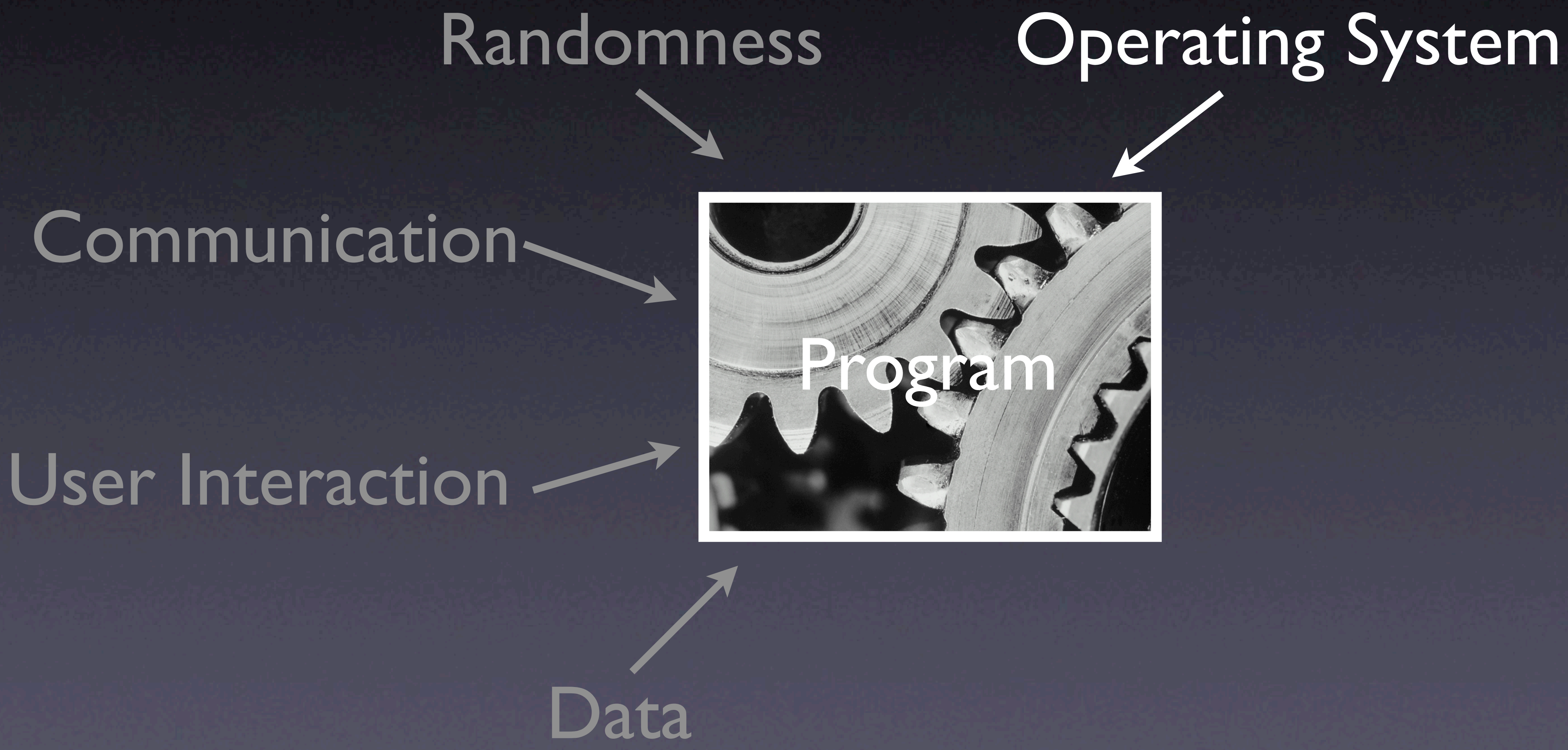
Randomness

- Program behaves different in every run
- Based on random number generator
  - Pseudo-random: save *seed* (and make it configurable)
    - Same applies to *time of day*
  - True random: record + replay sequence

Program Inputs



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Operating System

- The OS handles *entire* interaction between program and environment
- Recording and replaying OS interaction thus makes entire program run reproducible

A Password Program

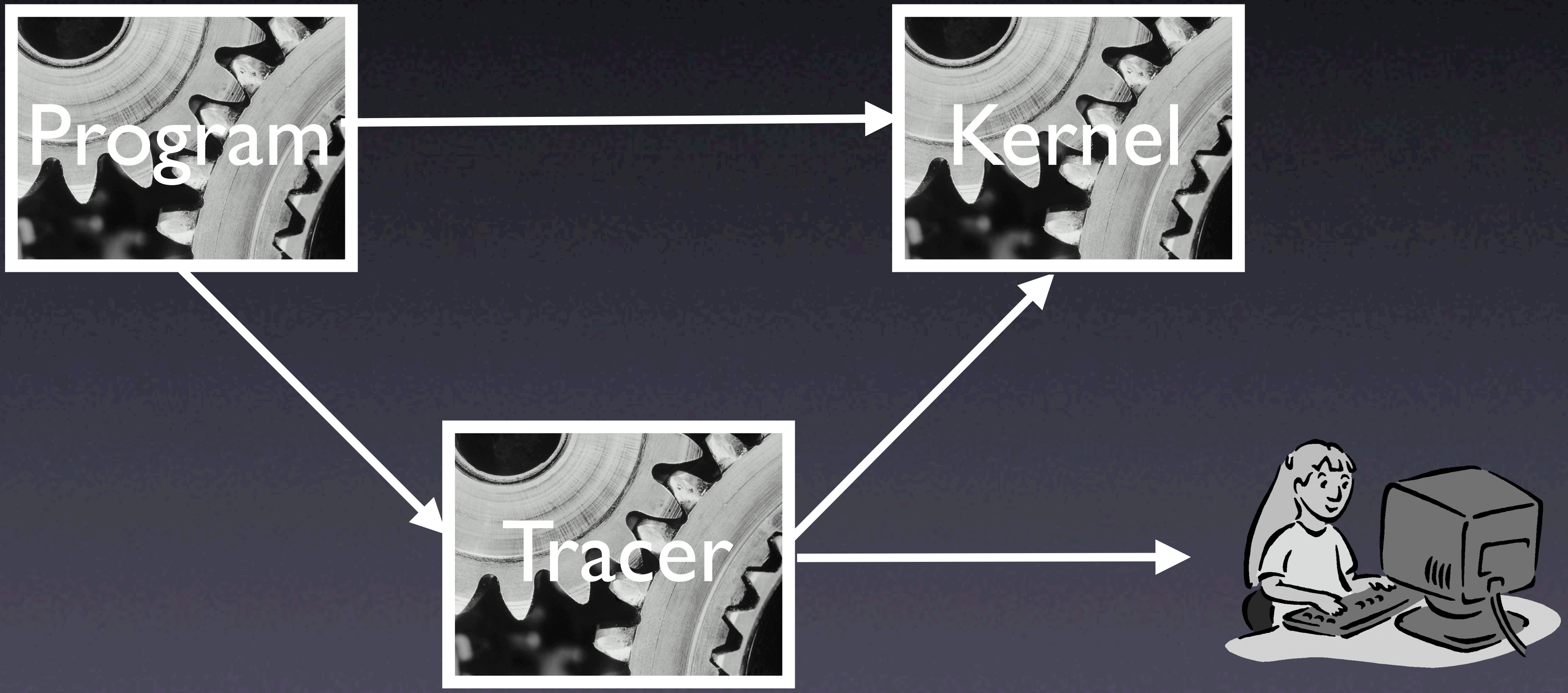
```
#include <string>
#include <iostream>
using namespace std;

string secret_password = "secret";

int main()
{
    string given_password;
    cout << "Please enter your password: ";
    cin >> given_password;
    if (given_password == secret_password)
        cout << "Access granted." << endl;
    else
        cout << "Access denied." << endl;
}
```

```
$ c++ -o password password.C
$ ./password
Enter your password: secret
Access granted.
$
```

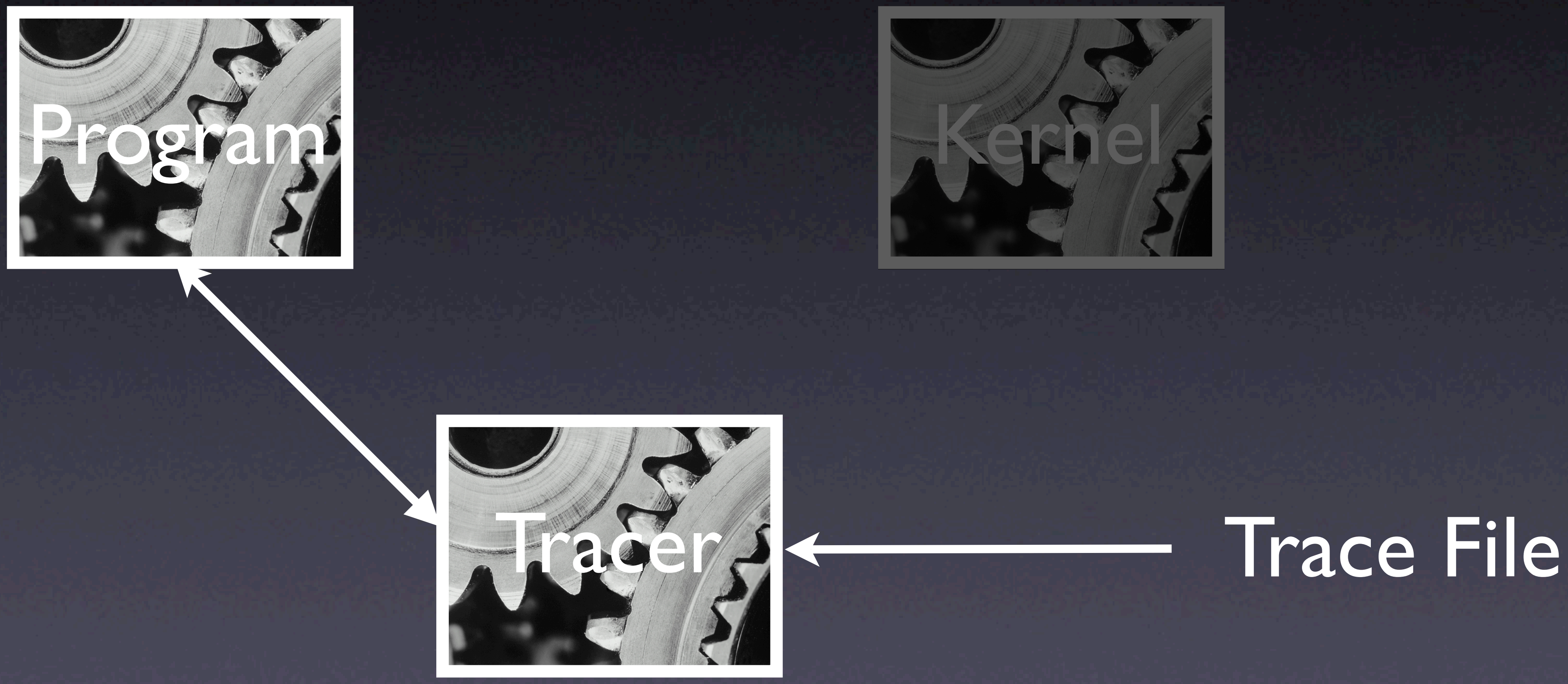
Traced Interaction

```
$ c++ -o password password.C
$ strace ./password 2> LOG
Enter your password: secret
Access granted.
$ cat LOG
...
write(1, "Please enter your password: ", 28) = 28
read(0, "secret\n", 1024)                   = 7
write(1, "Access granted.\n", 16)           = 16
exit_group(0)                               = ?
```

How Tracing works



Replaying Traces



Program

Kernel

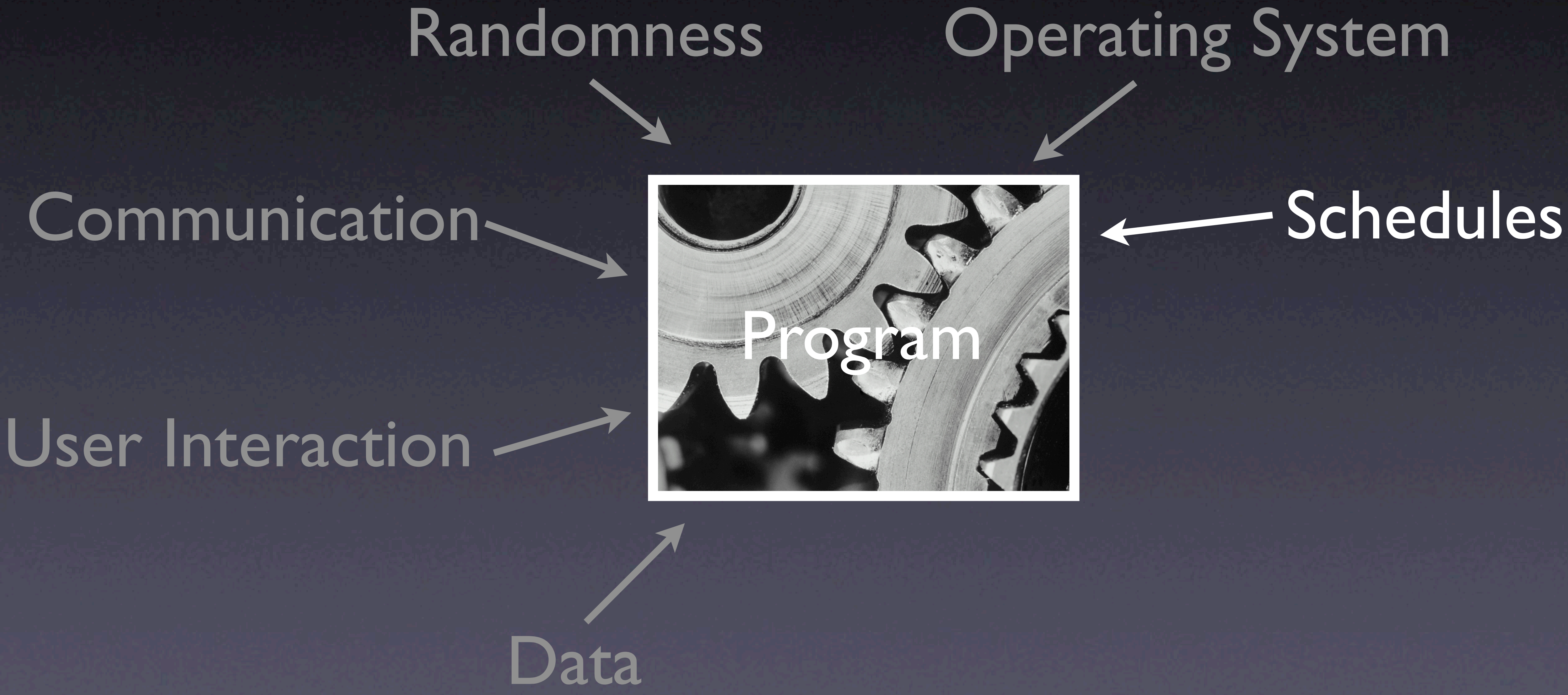
Tracer

Trace File

Challenges

- Tracing creates *lots* of data
- Example: Web server with 10 requests/sec
  A trace of 10 k/request means 8GB/day
- All of this must be *replayed* to reproduce the failure (alternative: *checkpoints*)
- Huge performance penalty!

Program Inputs



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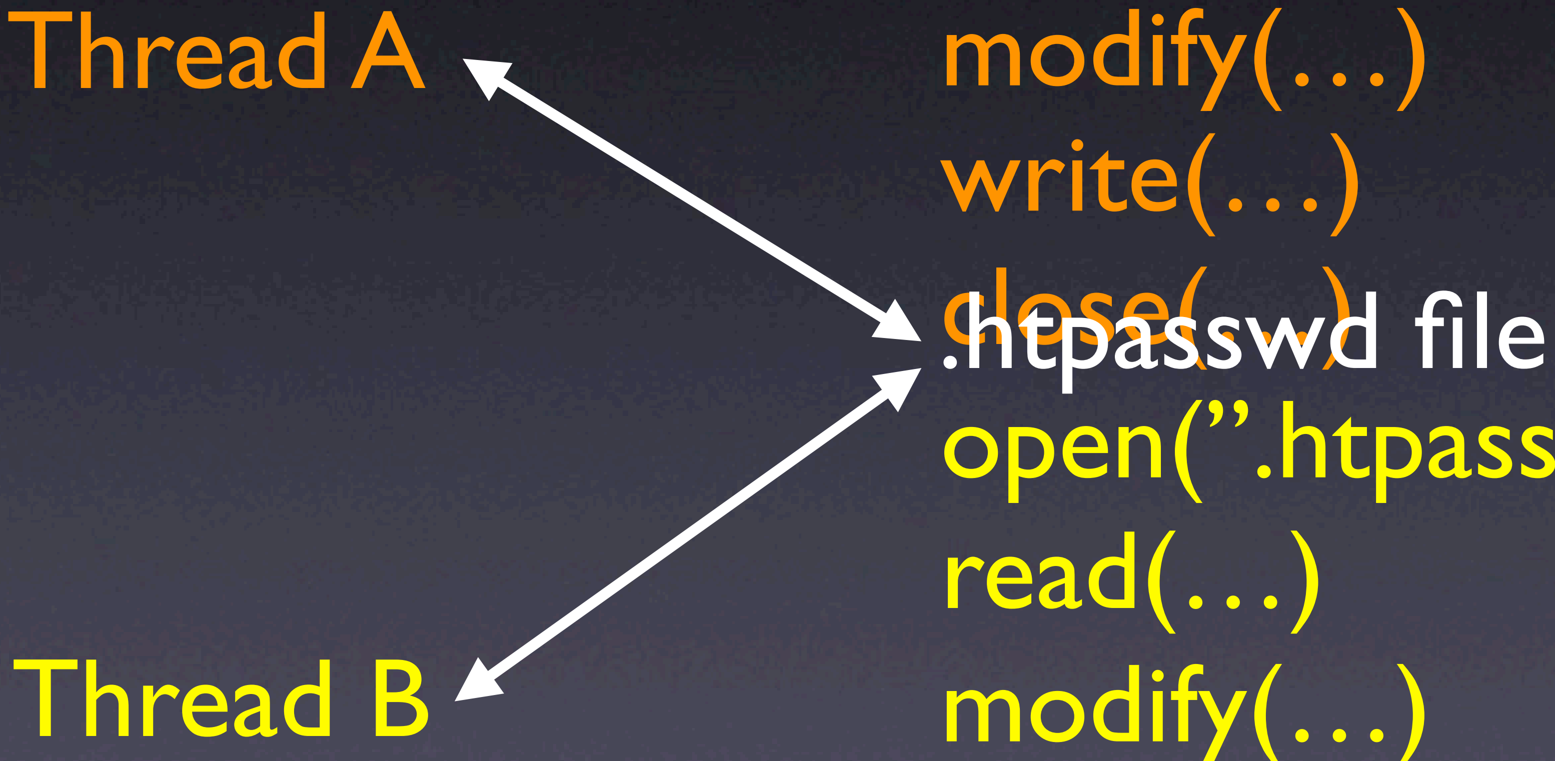
Accessing Passwords



Thread A

open(".htpasswd")
read(…)
modify(…)
write(…)
close(…)

.htpasswd file

Thread B

open(".htpasswd")
read(…)
modify(…)
write(…)
close(…)

Lost Update

open(".htpasswd")
open(".htpasswd")
Thread A read(…)
read(…)
modify(…)
write(…)
close(…)
Thread B modify(…)
write(…)
close(…)

A's updates get lost!

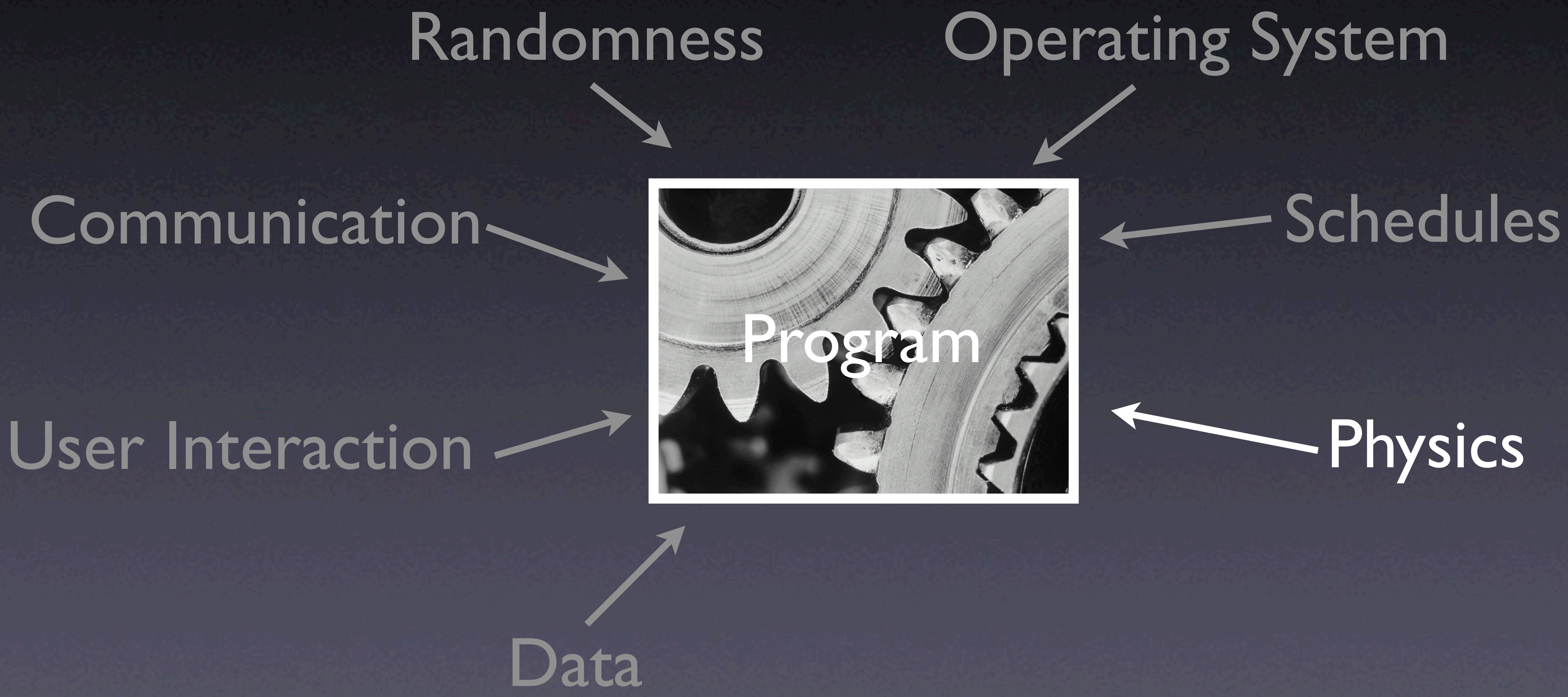
Reproducing Schedules

- Thread changes are induced by a *scheduler*
- It suffices to record the schedule (i.e. the moments in time at which thread switches occur) and to replay it
- Requires deterministic input replay

Constructive Solutions

- Lock resource before writing
- Check resource update time before writing
- … or any other *synchronization mechanism*

Program Inputs



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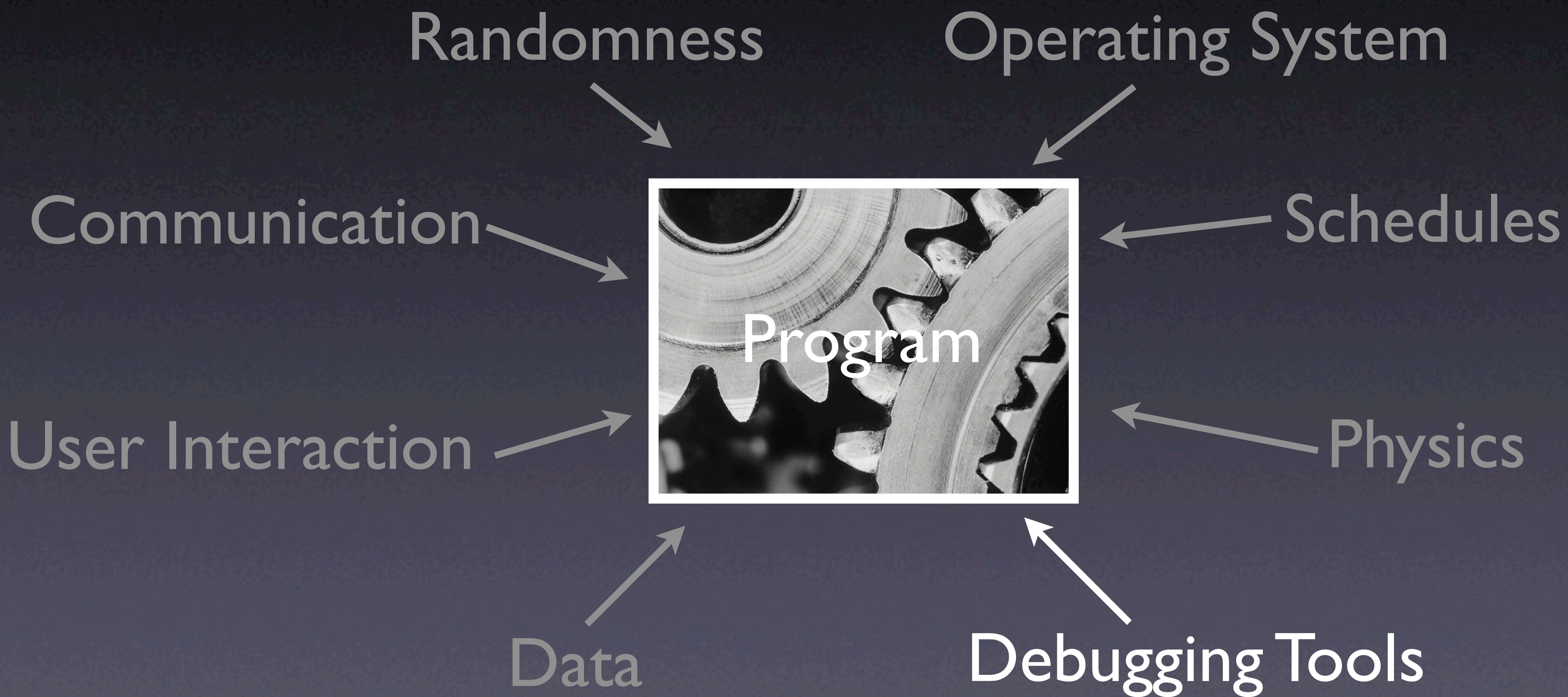
Physical Influences

- Static electricity
- Alpha particles (*not* cosmic rays)
- Quantum effects
- Humidity
- Mechanical failures + real bugs

Rare and hard to reproduce

Program Inputs



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Debugging Tools

A Heisenbug

- Code fails outside debugger only

```
int f() {
    int i;
    return i;
}
```

In program:
returns random value

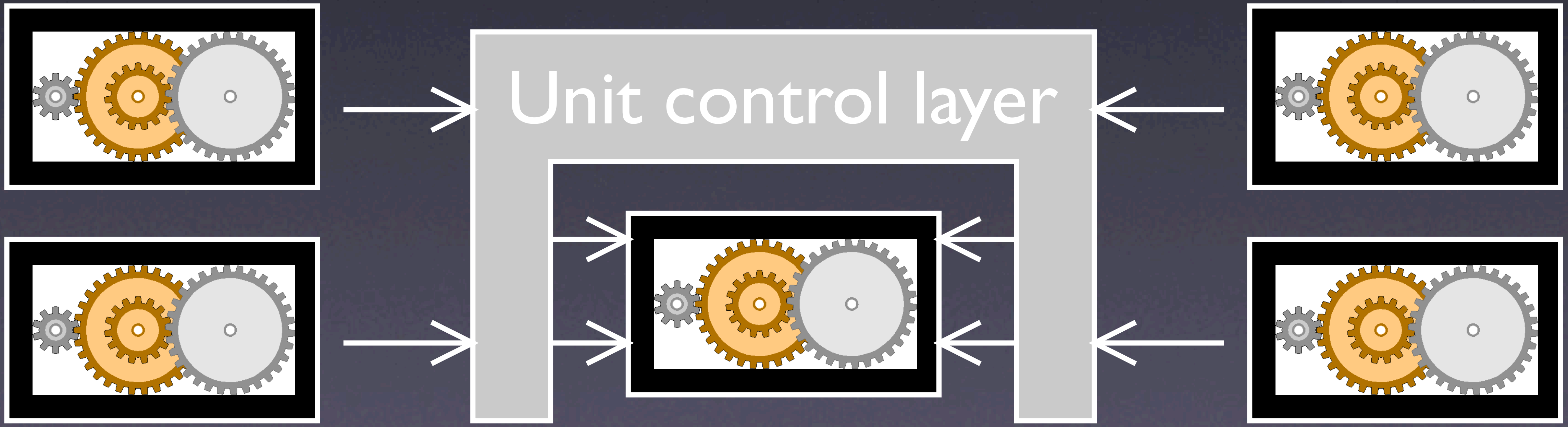
In debugger:
returns 0

More Bugs

Heisenbug	Bohr Bug
Mandelbug	Schrödinbug

Isolating Units

- Capture + replay *unit* instead of program
- Needs an *unit control layer* to monitor input



Isolated Units

- Databases. Replay only the interaction with the database.
- Compilers. Record + replay intermediate data structures rather than the entire front-end.
- Networking. Record + replay communication calls.

A Control Example

```
class Map {
public:
    virtual void add(string key, int value);
    virtual void del(string key);
    virtual int lookup(string key);
};
```

- How do we control this?

A Log as a Program

```
#include "Map.h"
#include <assert>

int main() {
    Map map;
    map.add("onions", 4);
    map.del("truffels");
    assert(map.lookup("onions") == 4);
    return 0;
}
```

- This is a log file (and also a program)
- How do we get this?

Controlled Map

```
class ControlledMap: public Map {
public:
    typedef Map super;

    virtual void add(string key, int value);
    virtual void del(string key);
    virtual int lookup(string key);

    ControlledMap();            // Constructor
    ~ControlledMap();           // Destructor
};
```

Logging

```
void ControlledMap::add(string key, int value) {
    clog << "map.add(\"" << key << "\", "
         << value << ");" << endl;
    Map::add(key, value);
}                                      map.add("onions", 4);

void ControlledMap::del(string key) {
    clog << "map.del(\"" << key << "\");" << endl;
    Map::del(key);
}                                       map.del("truffels");

virtual int ControlledMap::lookup(string key) {
    clog << "assert(map.lookup(\"" << key << "\") == ";
    int ret = Map::lookup(key);
    clog << ret << ");" << endl;
    return ret;
}                           assert(map.lookup("onions") == 4);
```

Logging Fixture

```
ControlledMap::ControlledMap()
{
    clog << "#include \"Map.h\"" << endl
         << "#include <assert>" << endl
         << "" << endl
         << "int main() {" << endl
         << "    Map map;" << endl;
}

ControlledMap::~ControlledMap()
{
    clog << "    return 0;" << endl;
         << "}" << endl;
}
```

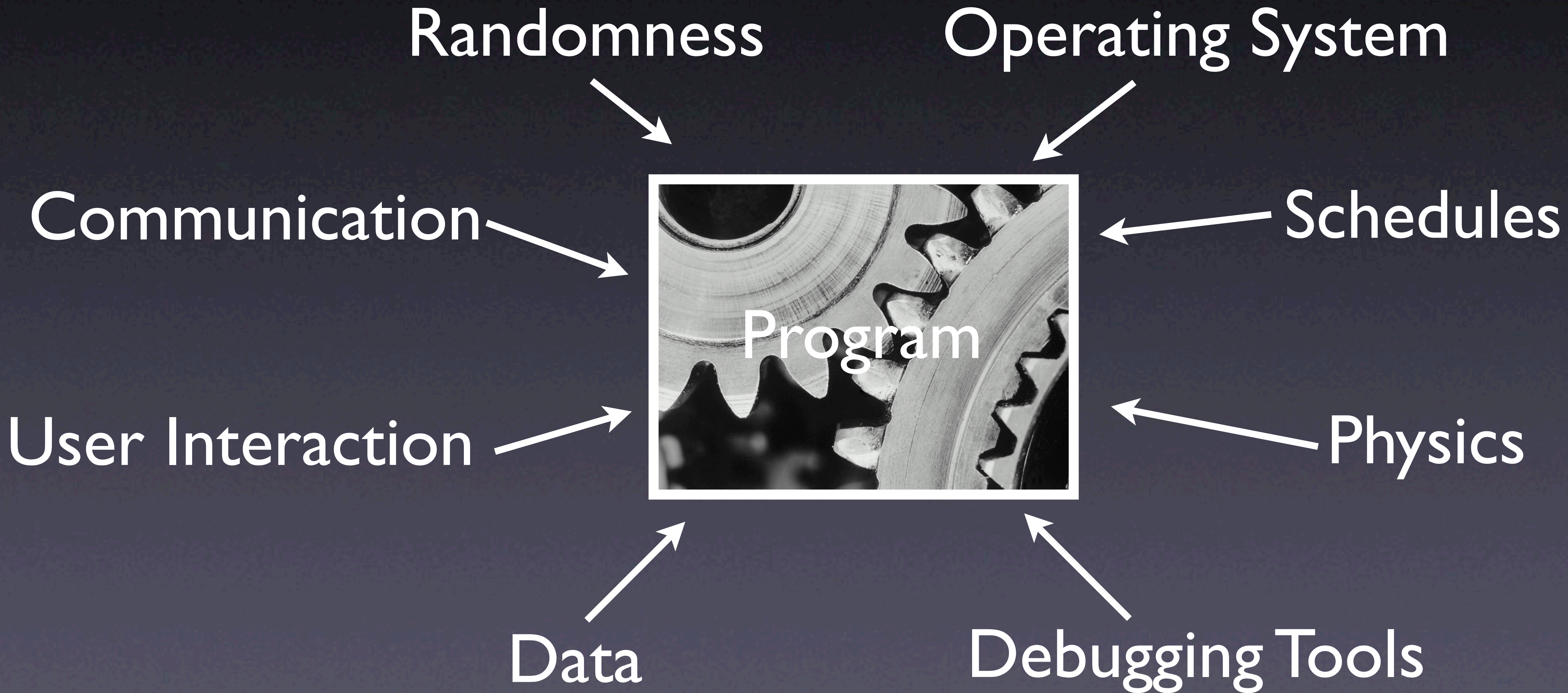
More Interaction

- Variables (hard to detect)
- Other units (break dependency if needed)
- Time (record + replay, too)

Concepts

- Once a problem is tracked, one must *reproduce it* in the own environment
- To reproduce a problem…
    - reproduce the *environment* (by adopting one circumstance after the other)
    - reproduce the *execution* (by controlling the input of the program or a unit)

Program Inputs



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