

Inside a VM -3

With Cliff Click

What Is a (Virtual) Machine?

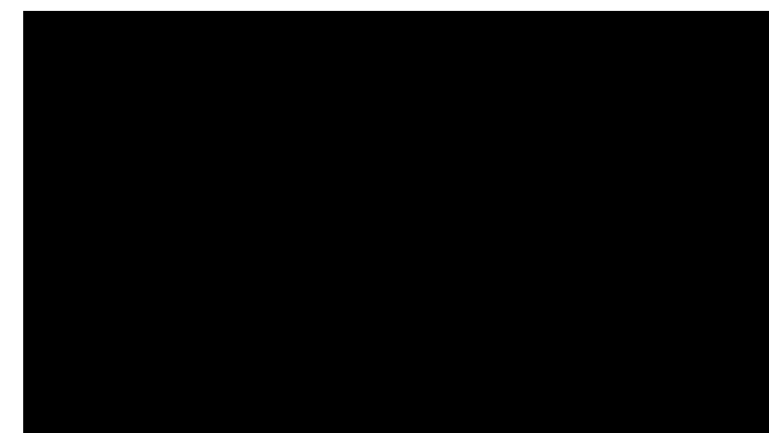
Well, what's a Machine?

A Program?

You all know it... in your gut

Lets make sure you know it...in your head

Because there's a little bit of "the Matrix" and Gödel in there...



P

P = Program

```
int main() {  
    printf("hello world");  
}
```

P = Program

```
int main() {  
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}
```

```
mov    eax,3  
mov    ebx,[eax]  
mov    [esi+4*ebx],5
```

P = Program

```
int main() {  
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```
mov    eax,3  
mov    ebx,[eax]  
mov    [esi+4*ebx],5
```

2 cups flour
½ cup sugar
½ cup brown sugar
....

P = Program

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int main() {
    printf("hello world");
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mov    eax,3
mov    ebx,[eax]
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P = Program

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Form 1040EZ

Department of the Treasury—Internal Revenue Service

Income Tax Return for Single and Joint Filers With No Dependents (99)

2015

OMB No. 1545-0074

Your first name and initial

Last name

Your social security number

If a joint return, spouse's first name and initial

Last name

Spouse's social security number

Home address (number and street). If you have a P.O. box, see instructions.

Apt. no.

▲ Make sure the SSN(s) above are correct.

City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).

Presidential Election Campaign

Foreign country name

Foreign province/state/county

Foreign postal code

Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund. ☐ You ☐ Spouse

Income

1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2.

1

2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ.

2

3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions).

3

4 Add lines 1, 2, and 3. This is your adjusted gross income.

4

5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back.
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If no one can claim you (or your spouse if a joint return), enter \$10,300 if single; \$20,600 if married filing jointly. See back for explanation.

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6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your taxable income.

6

7 Federal income tax withheld from Form(s) W-2 and 1099.

7

8a Earned income credit (EIC) (see instructions)

8a

8b Nontaxable combat pay election.

8b

9 Add lines 7 and 8a. These are your total payments and credits.

9

10 Tax. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line.

10

Payments, Credits, and Tax

11


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A recipe for getting something done

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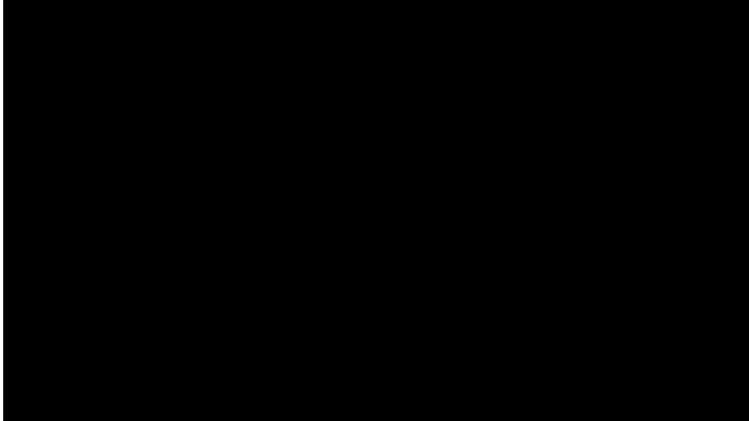
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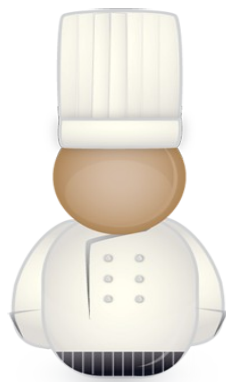


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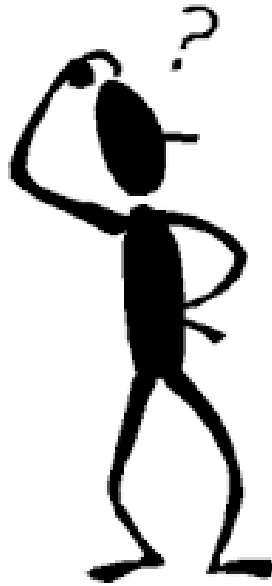
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mov    eax, 3
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M = Machine

2 cups flour
½ cup sugar
½ cup brown sugar



An actor that follows instructions to change the physical world

....

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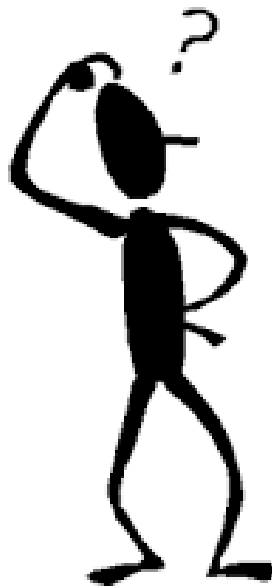
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A = Answer

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browser
email
hello world
database
games

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8a **Earned income credit (EIC)** (see instructions) 8a

b Nontaxable combat pay election. 8b

9 Add lines 7 and 8a. These are your **total payments and credits**. 9

10 **Tax**. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line. 10

11 **Refund**. If you are entitled to a refund, enter the amount from line 10. If you owe tax, enter the amount from line 10. 11

```
int main() {
    printf("hello world");
}
```



browser
email
hello world
database
games

```
mov    eax, 3
mov    ebx, [eax]
mov    [esi+4*ebx], 5
```



A = Answer

2 cups flour
½ cup sugar
½ cup brown sugar



....

Form 1040EZ Department of the Treasury—Internal Revenue Service
Income Tax Return for Single and Joint Filers With No Dependents (99) 2015 OMB No. 1545-0074

Your first name and initial Last name Your social security number

If a joint return, spouse's first name and initial Last name Spouse's social security number

Home address (number and street). If you have a P.O. box, see instructions. Apt. no. Make sure the SSN(s) above are correct.

City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).

Foreign country name Foreign province/state/county Foreign postal code Presidential Election Campaign Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund. ☐ You ☐ Spouse

Income 1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. 1

Attach Form(s) W-2 here. 2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ. 2

Enclose, but do not attach, any payment. 3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions). 3

4 Add lines 1, 2, and 3. This is your **adjusted gross income**. 4

5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back. 5

☐ You ☐ Spouse If no one can claim you (or your spouse if a joint return), enter \$10,300 if single; \$20,600 if **married filing jointly**. See back for explanation.

6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your **taxable income**. 6

Payments, Credits, and Tax 7 Federal income tax withheld from Form(s) W-2 and 1099. 7

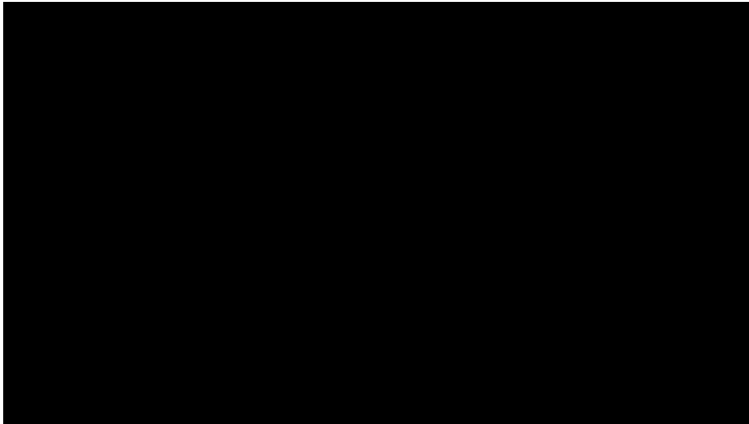
8a **Earned income credit (EIC)** (see instructions) 8a

b Nontaxable combat pay election. 8b

9 Add lines 7 and 8a. These are your **total payments and credits**. 9

10 **Tax**. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line. 10

11 **Refund** (see instructions) 11




```
int main() {
    printf("hello world");
}
```



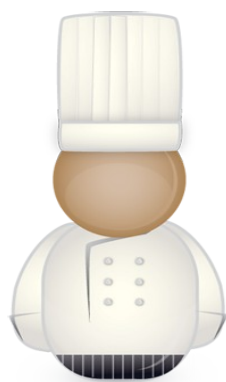
browser
email
hello world
database
games

```
mov    eax, 3
mov    ebx, [eax]
mov    [esi+4*ebx], 5
```



A = Answer

2 cups flour
½ cup sugar
½ cup brown sugar



....

Form 1040EZ Department of the Treasury—Internal Revenue Service Income Tax Return for Single and Joint Filers With No Dependents (99) 2015 OMB No. 1545-0074

Your first name and initial Last name Your social security number

If a joint return, spouse's first name and initial Last name Spouse's social security number

Home address (number and street). If you have a P.O. box, see instructions. Apt. no. Make sure the SSN(s) above are correct.

City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).

Foreign country name Foreign province/state/county Foreign postal code Presidential Election Campaign Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund. ☐ You ☐ Spouse

Income 1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2. 1

2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ. 2

3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions). 3

4 Add lines 1, 2, and 3. This is your **adjusted gross income**. 4

5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back. ☐ You ☐ Spouse If no one can claim you (or your spouse if a joint return), enter \$10,300 if **single**; \$20,600 if **married filing jointly**. See back for explanation. 5

6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your **taxable income**. 6

7 Federal income tax withheld from Form(s) W-2 and 1099. 7

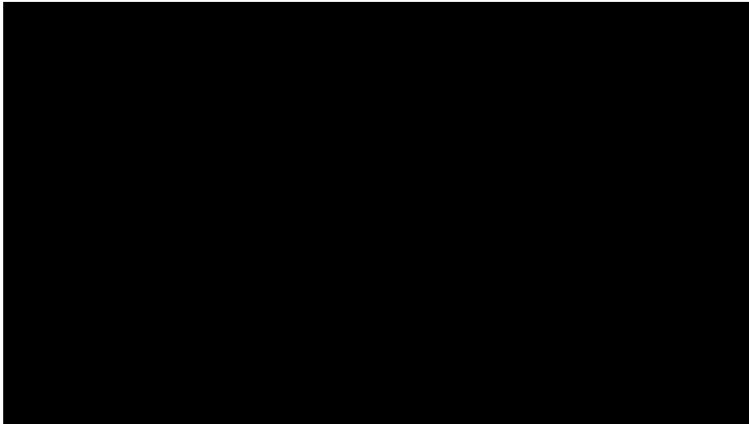
8a **Earned income credit (EIC)** (see instructions) 8a

8b Nontaxable combat pay election. 8b

9 Add lines 7 and 8a. These are your **total payments and credits**. 9

10 **Tax**. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line. 10

11 **Refund or amount you paid over** (see instructions). If you have a refund, enter the amount. If you paid over, enter the amount. 11



$$P \rightarrow M \rightarrow A$$

$$P \rightarrow M \rightarrow A$$

Program: Defined by rules we make up; Easy to change

Software

$$P \rightarrow M \rightarrow A$$

Program: Defined by rules we make up; Easy to change

Software

Machine: Define by physics; Hard to change

Hardware

$$P \rightarrow M \rightarrow A$$

Program: Defined by rules we make up; Easy to change

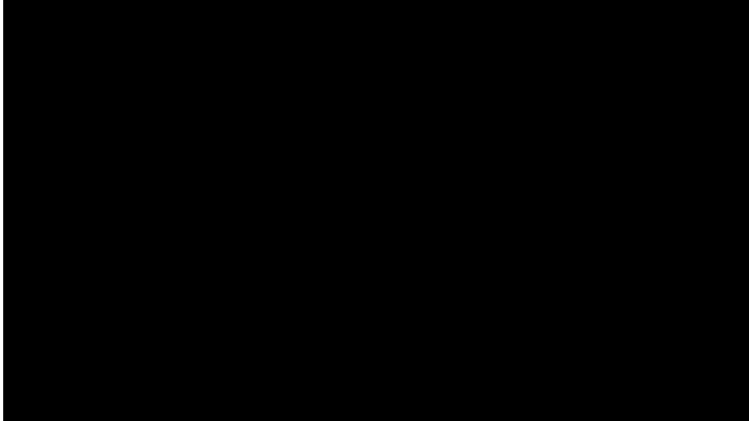
Software

Machine: Define by physics; Hard to change

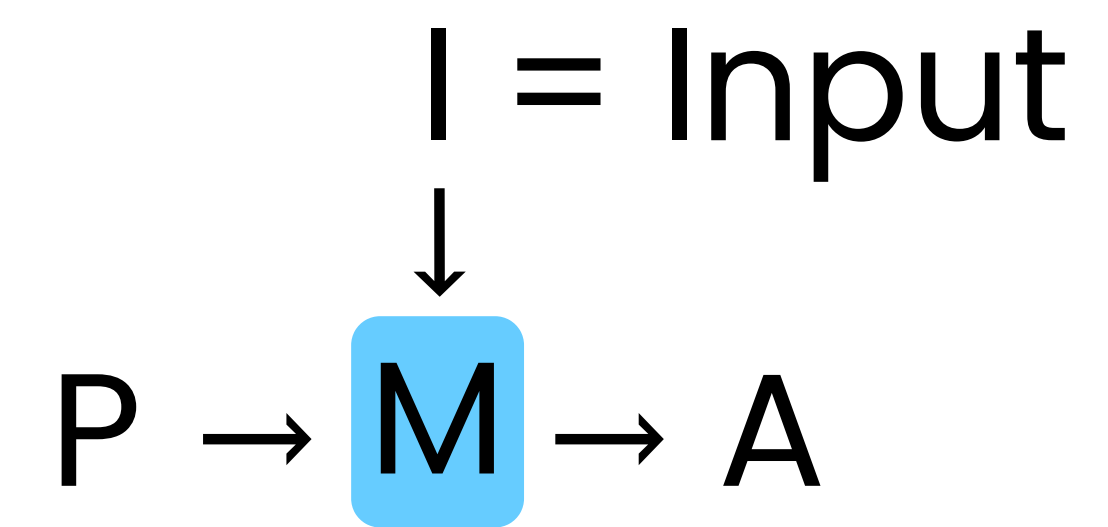
Hardware

Answer: What We Want

I



I = Input



```
int main() {
    printf("hello world");
}
```

```
mov    eax,3
mov    ebx,[eax]
mov    [esi+4*ebx],5
```

- 2 cups flour
- ½ cup sugar
- ½ cup brown sugar

....

Form 1040EZ

Department of the Treasury—Internal Revenue Service

Income Tax Return for Single and Joint Filers With No Dependents (99)

2015

OMB No. 1545-0074

Your first name and initial

Last name

Your social security number

If a joint return, spouse's first name and initial

Last name

Spouse's social security number

Home address (number and street). If you have a P.O. box, see instructions.

Apt. no.

▲ Make sure the SSN(s) above are correct.

City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).

Presidential Election Campaign

Foreign country name

Foreign province/state/country

Foreign postal code

Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund. ☐ You ☐ Spouse

Income

1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2.

1

2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ.

2

3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions).

3

4 Add lines 1, 2, and 3. This is your adjusted gross income.

4

5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back.
☐ You ☐ Spouse
If no one can claim you (or your spouse if a joint return), enter \$10,300 if single; \$20,600 if married filing jointly. See back for explanation.

5

6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your taxable income.

6

7 Federal income tax withheld from Form(s) W-2 and 1099.

7

8a Earned income credit (EIC) (see instructions)

8a

b Nontaxable combat pay election. 8b

9 Add lines 7 and 8a. These are your total payments and credits.

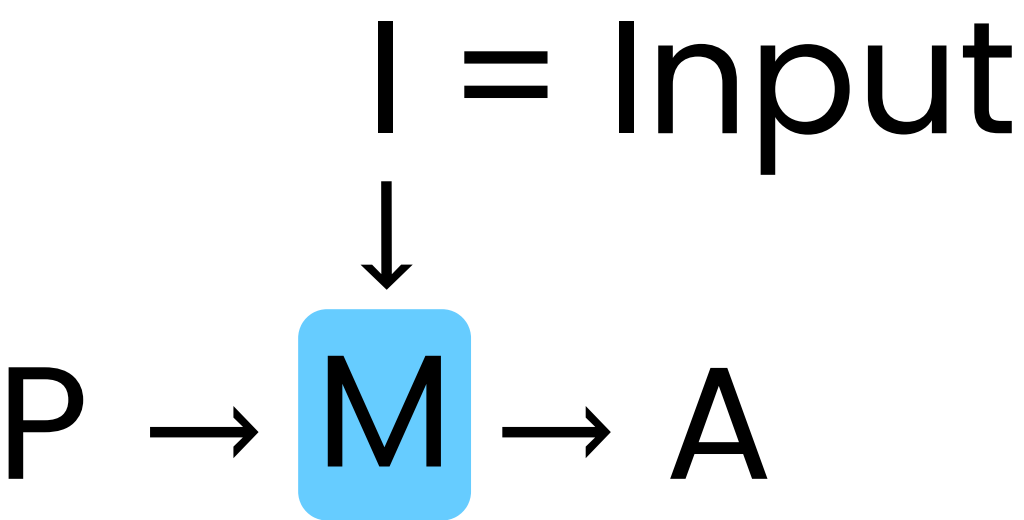
9

10 Tax. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line.

10

Payments, Credits, and Tax

11




```
int main() {
    printf("hello world");
}
```

```
mov    eax,3
mov    ebx,[eax]
mov    [esi+4*ebx],5
```

- 2 cups flour
- ½ cup sugar
- ½ cup brown sugar

....

Form 1040EZ

Department of the Treasury—Internal Revenue Service

Income Tax Return for Single and Joint Filers With No Dependents (99)

2015

OMB No. 1545-0074

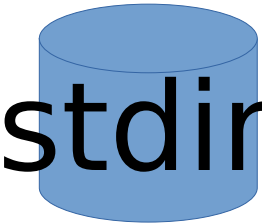
Your first name and initial		Last name		Your social security number	
If a joint return, spouse's first name and initial		Last name		Spouse's social security number	
Home address (number and street). If you have a P.O. box, see instructions.			Apt. no.	▲ Make sure the SSN(s) above are correct.	
City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).			Presidential Election Campaign		
Foreign country name		Foreign province/state/county		Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund.	
				<input type="checkbox"/> You <input type="checkbox"/> Spouse	

Income

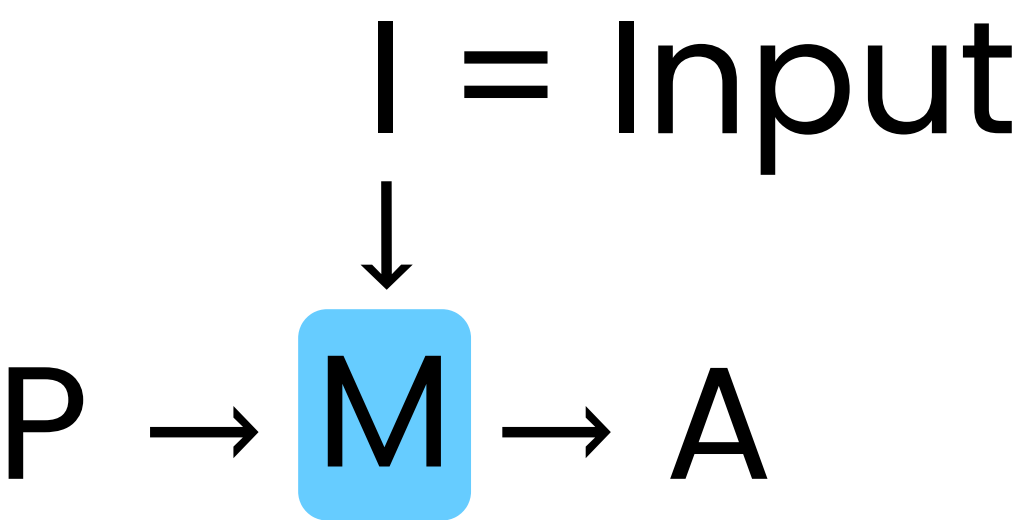
Attach Form(s) W-2 here.

Enclose, but do not attach, any payment.

1	Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2.	1	
2	Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ.	2	
3	Unemployment compensation and Alaska Permanent Fund dividends (see instructions).	3	
4	Add lines 1, 2, and 3. This is your adjusted gross income .	4	
5	If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back. <input type="checkbox"/> You <input type="checkbox"/> Spouse If no one can claim you (or your spouse if a joint return), enter \$10,300 if single ; \$20,600 if married filing jointly . See back for explanation.	5	
6	Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your taxable income .	6	
7	Federal income tax withheld from Form(s) W-2 and 1099.	7	
8a	Earned income credit (EIC) (see instructions)	8a	
b	Nontaxable combat pay election.	8b	
9	Add lines 7 and 8a. These are your total payments and credits .	9	
10	Tax. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line.	10	
11	Estimated tax to be paid with payment (see instructions). Enter your payment.	11	



files, keystrokes, mouse clicks



```
int main() {
    printf("hello world");
}
```

```
mov    eax,3
mov    ebx,[eax]
mov    [esi+4*ebx],5
```

- 2 cups flour
- ½ cup sugar
- ½ cup brown sugar

....

Form 1040EZ

Department of the Treasury—Internal Revenue Service

Income Tax Return for Single and Joint Filers With No Dependents (99)

2015

OMB No. 1545-0074

Your first name and initial

Last name

Your social security number

If a joint return, spouse's first name and initial

Last name

Spouse's social security number

Home address (number and street). If you have a P.O. box, see instructions.

Apt. no.

Make sure the SSN(s) above are correct.

City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).

Presidential Election Campaign

Foreign country name

Foreign province/state/county

Foreign postal code

Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund.

Income

1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2 here.

2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ.

3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions).

4 Add lines 1, 2, and 3. This is your adjusted gross income.

5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back.
☐ You ☐ Spouse
If no one can claim you (or your spouse if a joint return), enter \$10,300 if single; \$20,600 if married filing jointly. See back for explanation.

6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your taxable income.

7 Federal income tax withheld from Form(s) W-2 and 1099.

8a Earned income credit (EIC) (see instructions)

8b Nontaxable combat pay election.

9 Add lines 7 and 8a. These are your total payments and credits.

10 Tax. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line.

11 Estimated tax to be paid (see instructions)

files, keystrokes, mouse clicks

sound waves, radio waves

I = Input

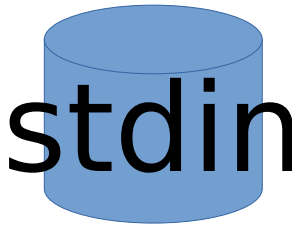
↓

P → M → A

```
int main() {
    printf("hello world");
}
```

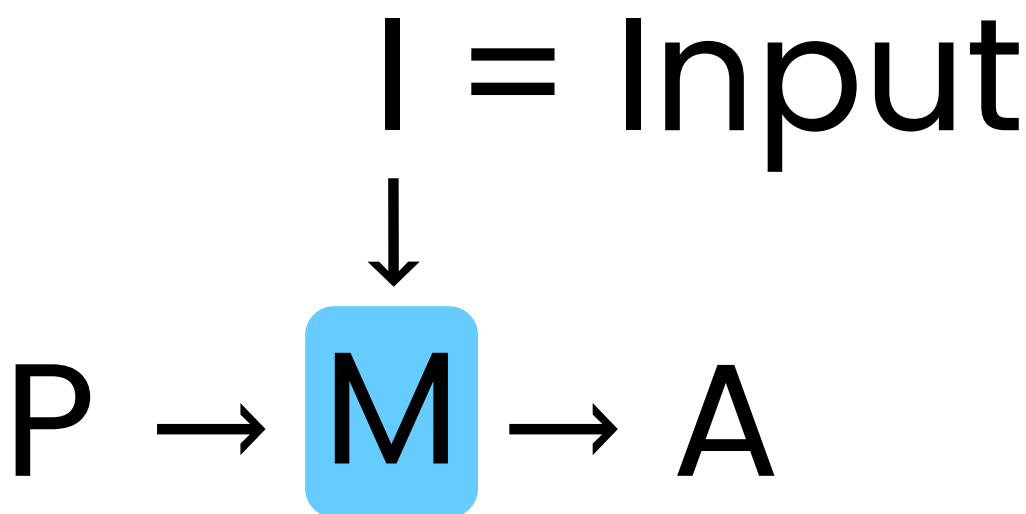
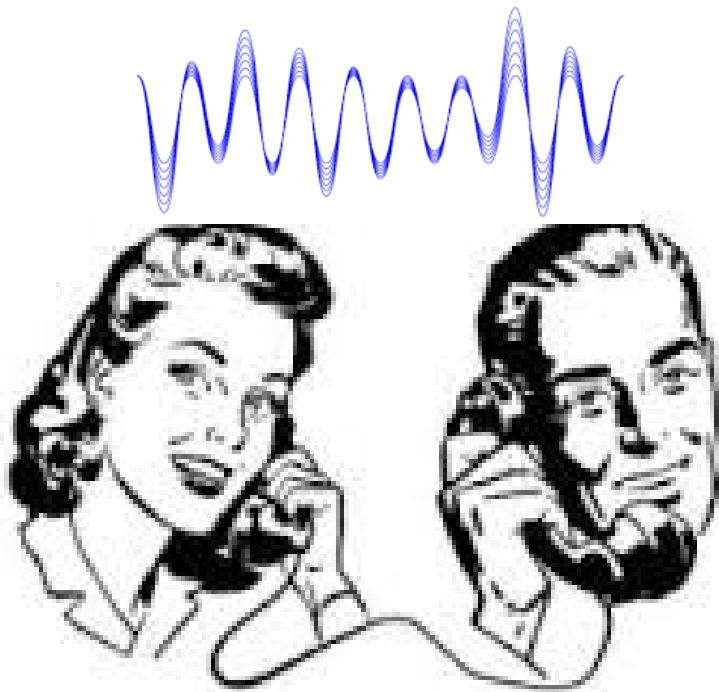
```
mov    eax,3
mov    ebx,[eax]
mov    [esi+4*ebx],5
```

2 cups flour
½ cup sugar
½ cup brown sugar
....



files, keystrokes, mouse clicks

sound waves, radio waves



flour, but also:
placement of flour container

Form 1040EZ Department of the Treasury—Internal Revenue Service 2015

OMB No. 1545-0074

Your first name and initial Last name Your social security number

If a joint return, spouse's first name and initial Last name Spouse's social security number

Home address (number and street). If you have a P.O. box, see instructions. Apt. no. Make sure the SSN(s) above are correct.

City, town or post office, state, and ZIP code. If you have a foreign address, also complete spaces below (see instructions).

Foreign country name Foreign province/state/county Foreign postal code Presidential Election Campaign Check here if you, or your spouse if filing jointly, want \$3 to go to this fund. Checking a box below will not change your tax or refund. ☐ You ☐ Spouse

Income

1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2. 1

2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ. 2

3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions). 3

4 Add lines 1, 2, and 3. This is your **adjusted gross income**. 4

5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back. ☐ You ☐ Spouse If no one can claim you (or your spouse if a joint return), enter \$10,300 if **single**; \$20,600 if **married filing jointly**. See back for explanation. 5

6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your **taxable income**. 6

7 Federal income tax withheld from Form(s) W-2 and 1099. 7

8a **Earned income credit (EIC)** (see instructions) 8a

b Nontaxable combat pay election. 8b

9 Add lines 7 and 8a. These are your **total payments and credits**. 9

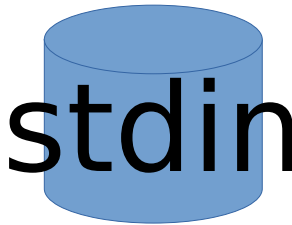
10 **Tax**. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line. 10

11 **Refundable credit** (see instructions) 11

```
int main() {
    printf("hello world");
}
```

```
mov    eax, 3
mov    ebx, [eax]
mov    [esi+4*ebx], 5
```

2 cups flour
½ cup sugar
½ cup brown sugar
....



files, keystrokes, mouse clicks

sound waves, radio waves



I = Input



flour, but also:
placement of flour container

Form 1040EZ		Department of the Treasury—Internal Revenue Service		Income Tax Return for Single and Joint Filers With No Dependents (99)		2015		OMB No. 1545-0074	
Your first name and initial		Last name		Your social security number					
If a joint return, spouse's first name and initial		Last name		Spouse's social security number					
Home address (number and street). If you have a P.O. box, see instructions.				Apt. no.		▲ Make sure the SSN(s) above are correct.			
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Income		1 Wages, salaries, and tips. This should be shown in box 1 of your Form(s) W-2. Attach your Form(s) W-2 here.		1					
		2 Taxable interest. If the total is over \$1,500, you cannot use Form 1040EZ.		2					
		3 Unemployment compensation and Alaska Permanent Fund dividends (see instructions).		3					
		4 Add lines 1, 2, and 3. This is your adjusted gross income.		4					
		5 If someone can claim you (or your spouse if a joint return) as a dependent, check the applicable box(es) below and enter the amount from the worksheet on back. <input type="checkbox"/> You <input type="checkbox"/> Spouse If no one can claim you (or your spouse if a joint return), enter \$10,300 if single; \$20,600 if married filing jointly. See back for explanation.		5					
		6 Subtract line 5 from line 4. If line 5 is larger than line 4, enter -0-. This is your taxable income.		6					
		7 Federal income tax withheld from Form(s) W-2 and 1099.		7					
		8a Earned income credit (EIC) (see instructions)		8a					
		b Nontaxable combat pay election.		8b					
		9 Add lines 7 and 8a. These are your total payments and credits.		9					
		10 Tax. Use the amount on line 6 above to find your tax in the tax table in the instructions. Then, enter the tax from the table on this line.		10					
		11 Estimated tax to be paid (see instructions).		11					



income, state taxes,
married vs single

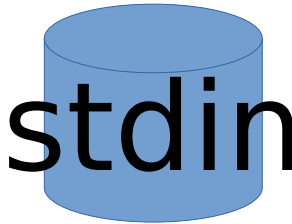

```
int main() {
    printf("hello world");
}
```

```
mov    eax,3
mov    ebx,[eax]
mov    [esi+4*ebx],5
```

2 cups flour
½ cup sugar
½ cup brown sugar
....



flour, but also:
placement of flour container

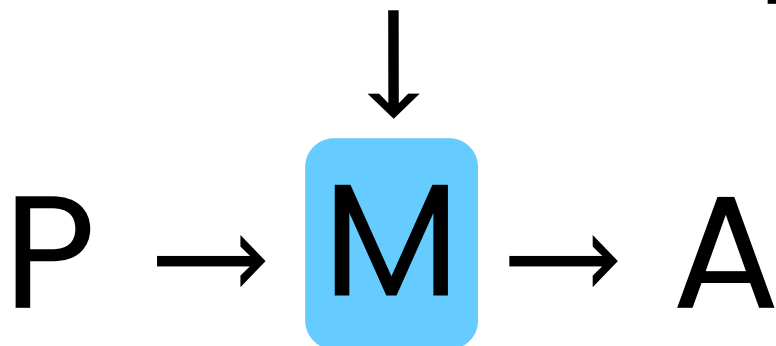


files, keystrokes, mouse clicks

sound waves, radio waves



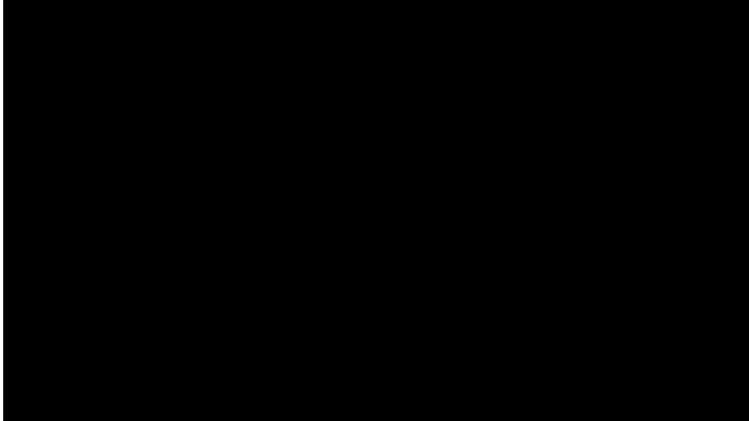
I = Input



income, state taxes,
married vs single

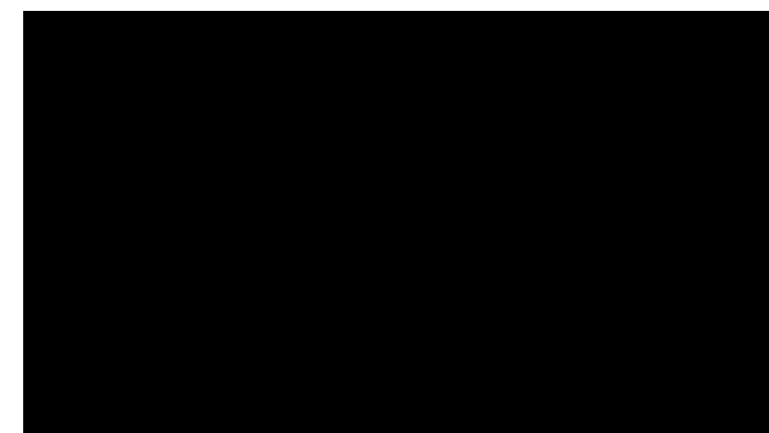
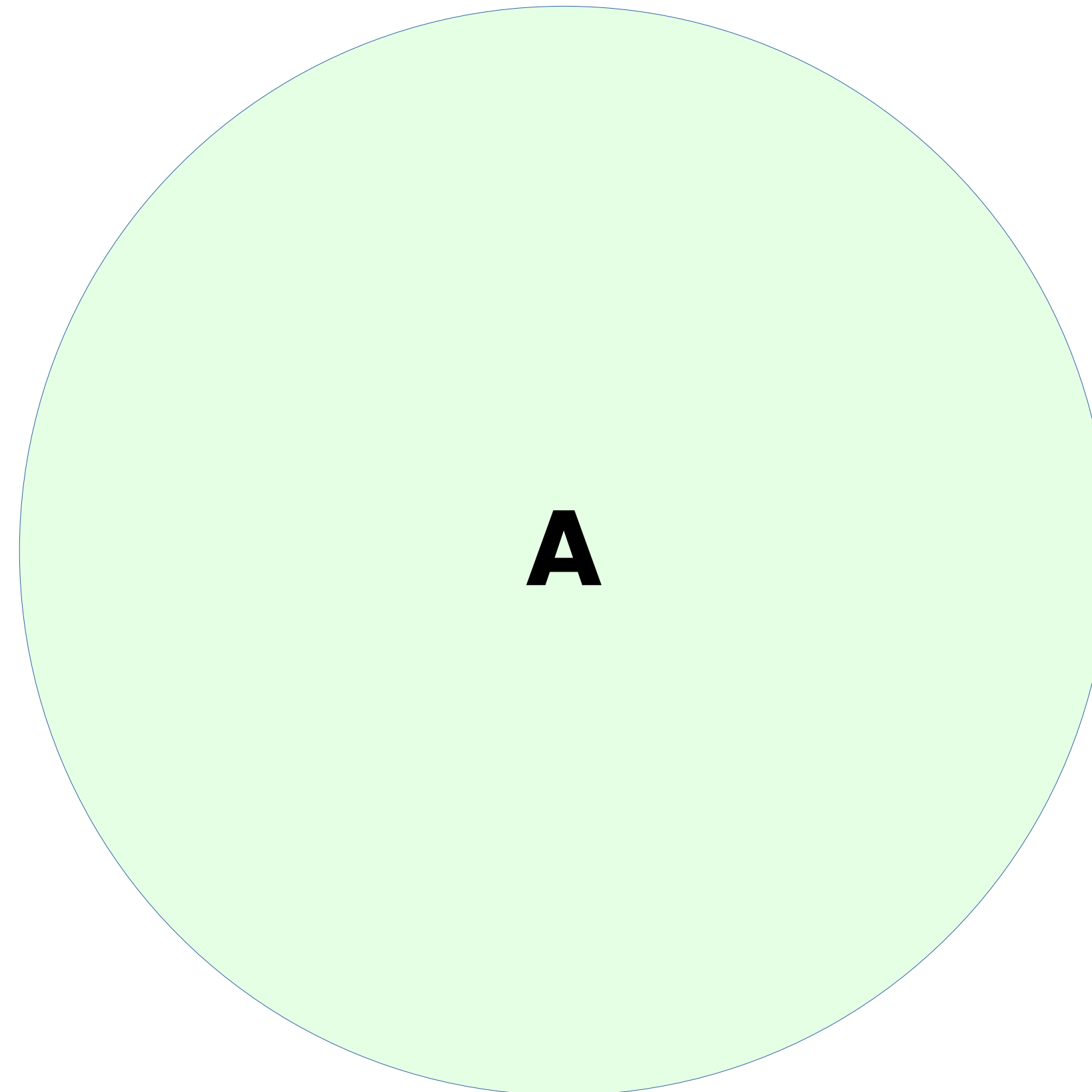
**Real-time state of physical world,
not part of the Program nor Machine**

And Output is...?



And Output is...?

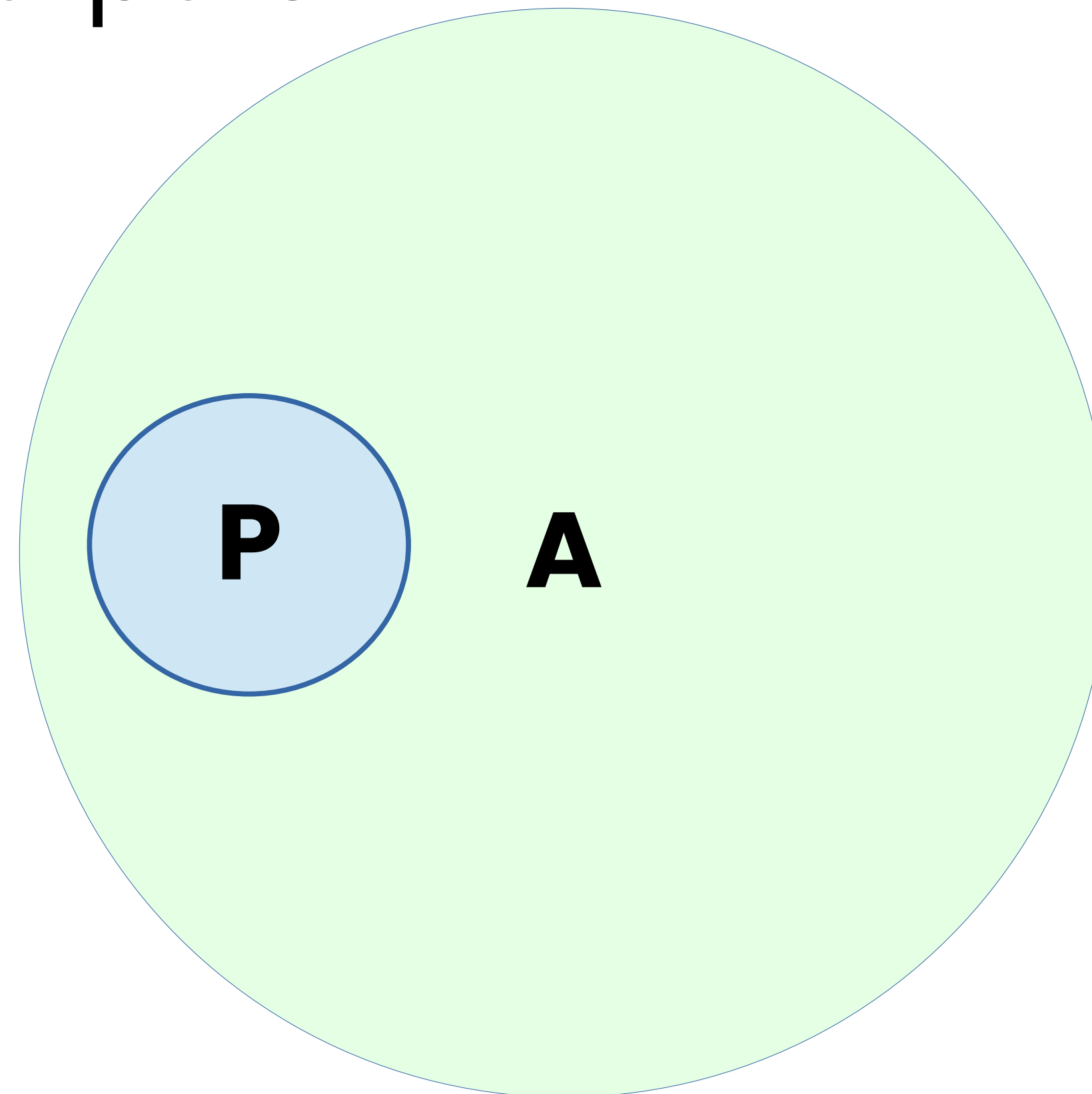
Just another Answer.



And Output is...?

Just another Answer.

Programs can be Outputs

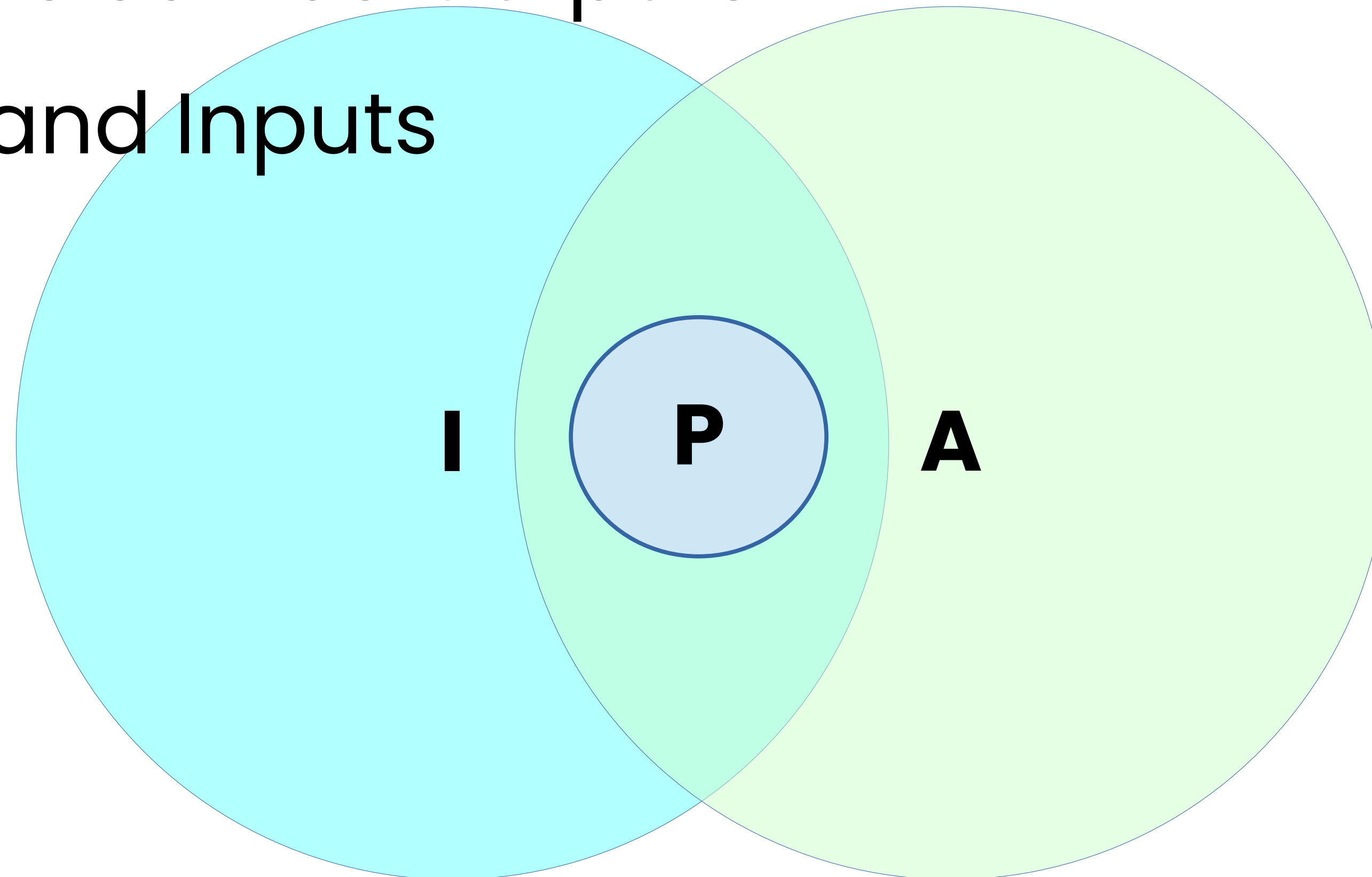


And Output is...?

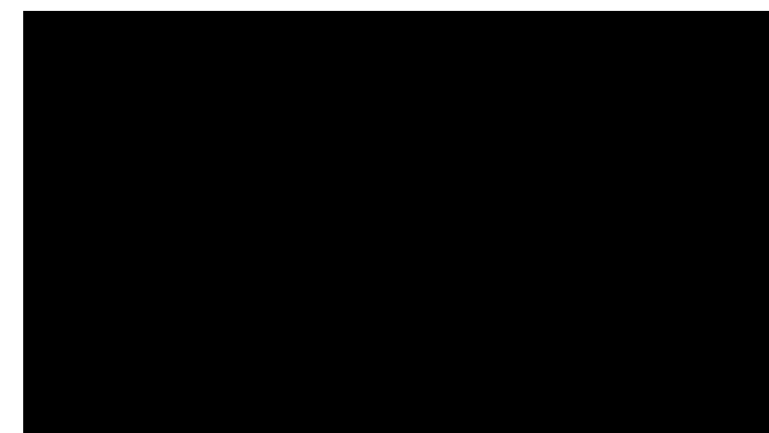
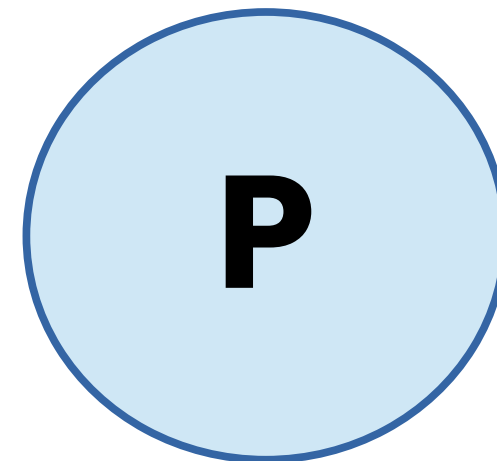
Just another Answer.

Programs can be Outputs

...and Inputs



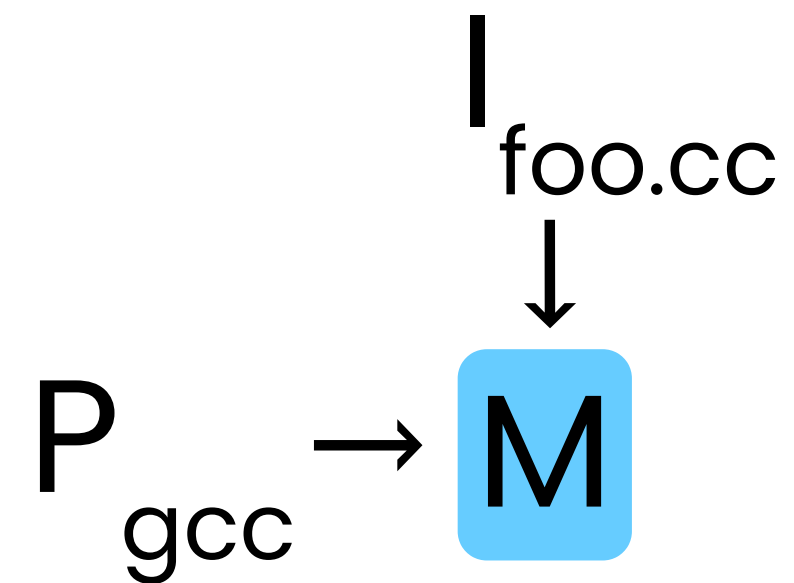
A Compiler is a Program



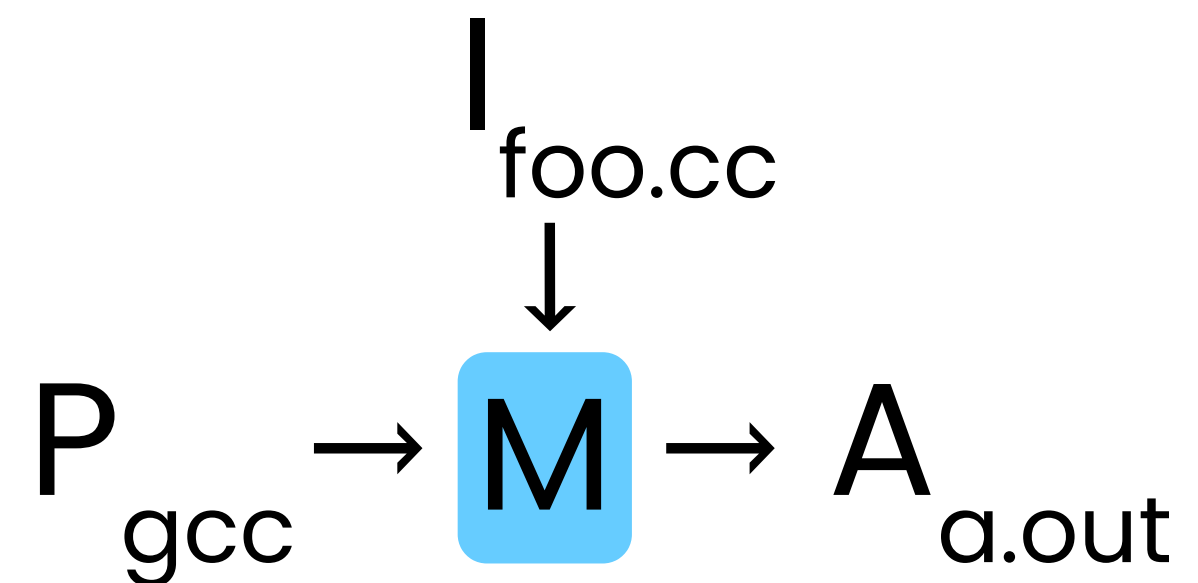
A Compiler (gcc) is a Program (gcc.exe)

P_{gcc}

A Compiler (`gcc`) is a Program (`gcc.exe`)
that changes a Program (`foo.cc`)

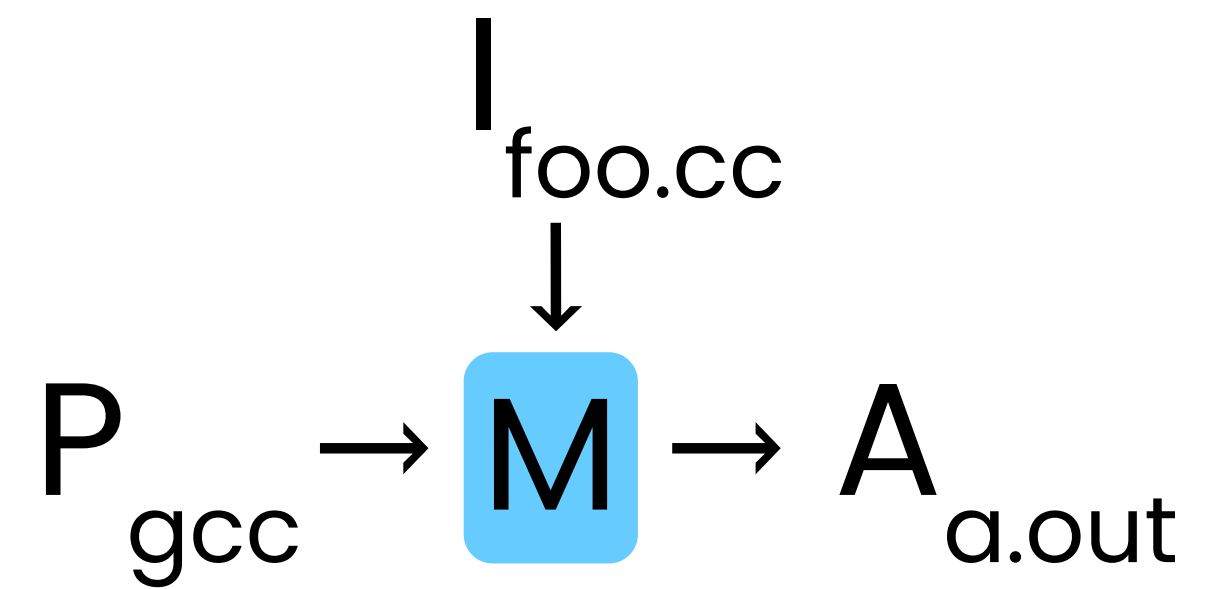


A Compiler (gcc) is a Program (gcc.exe)
that changes a Program (foo.cc)
into another Program (a.out)



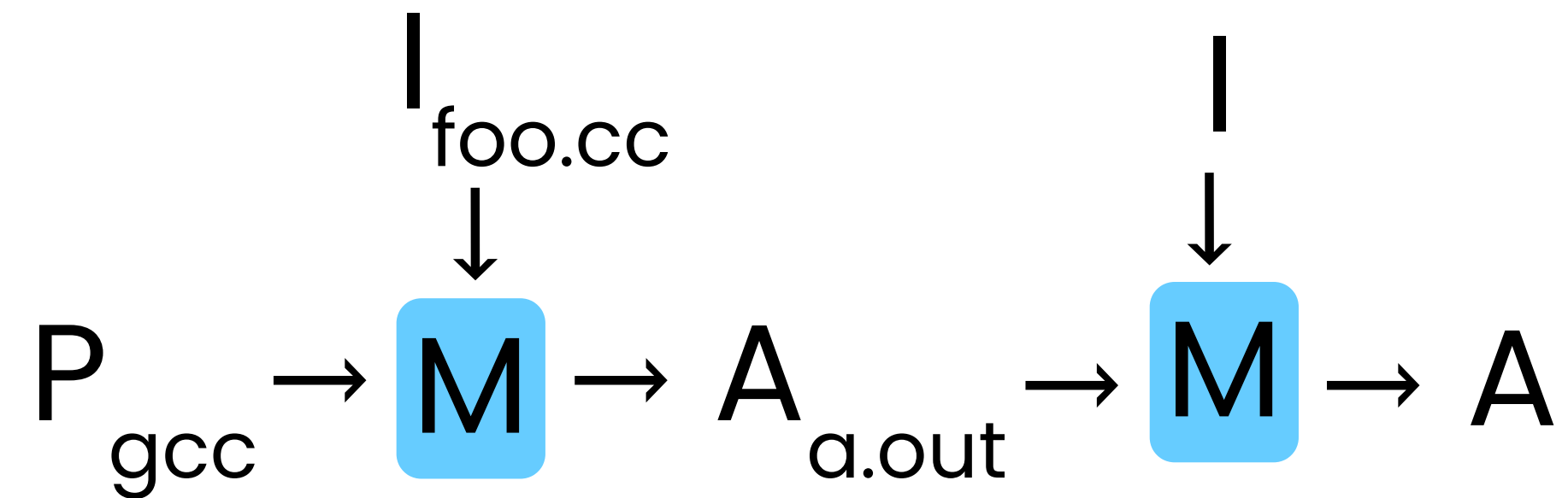
Compile: foo.cc → gcc → a.out

Compile.



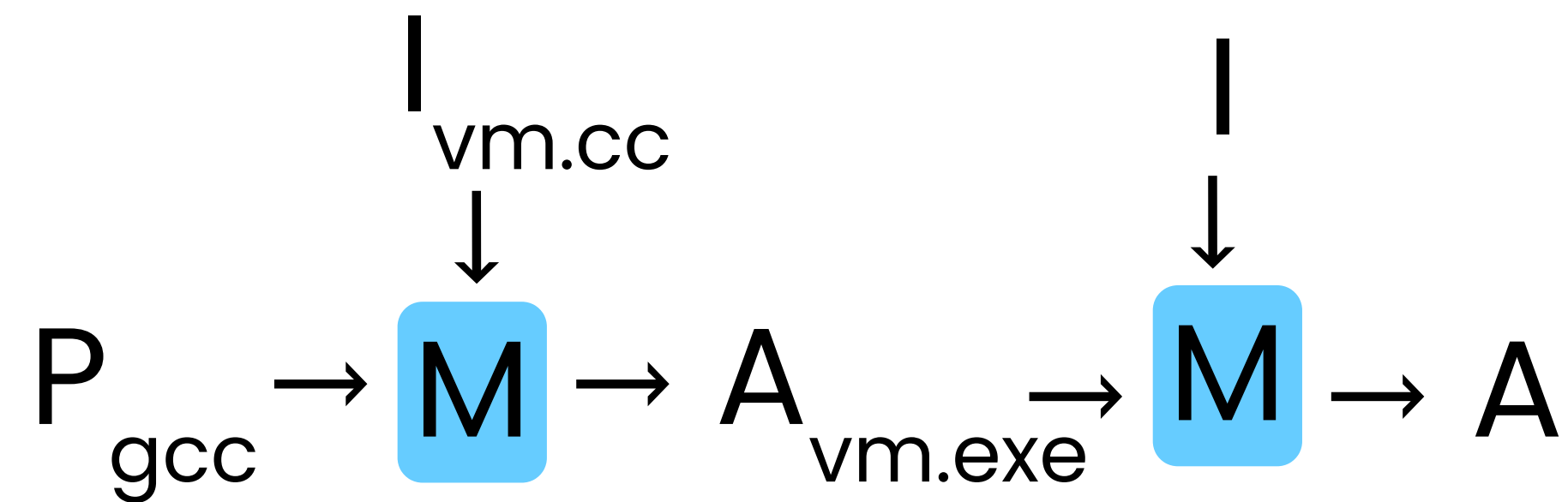
Compile: $foo.cc \rightarrow gcc \rightarrow a.out$

Compile. Then Run.



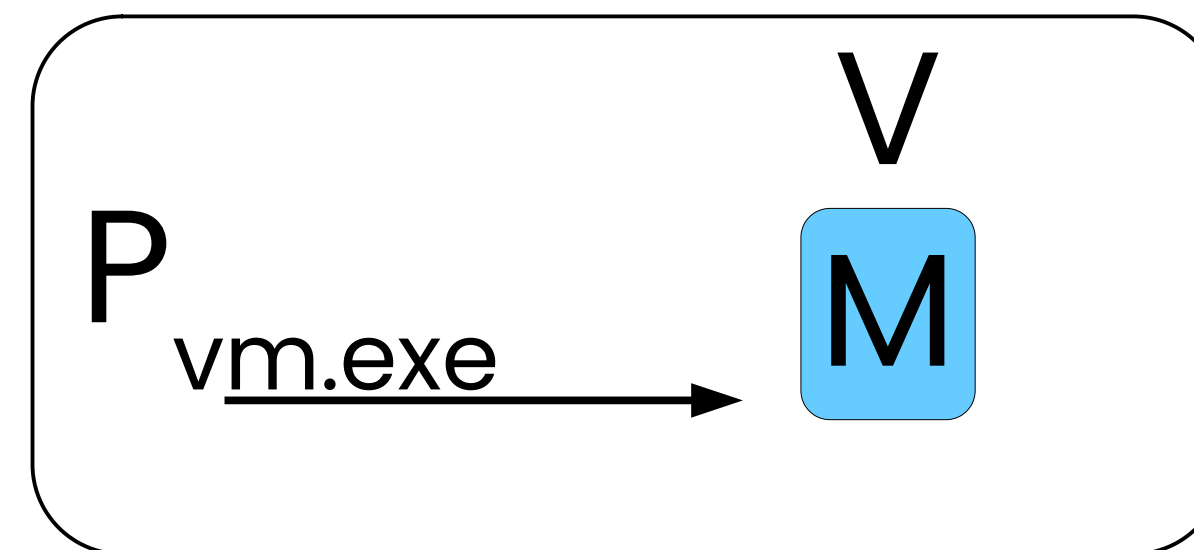
Compile: foo.cc → gcc → a.out **Run**: a.out → answer

A Virtual Machine is a Program

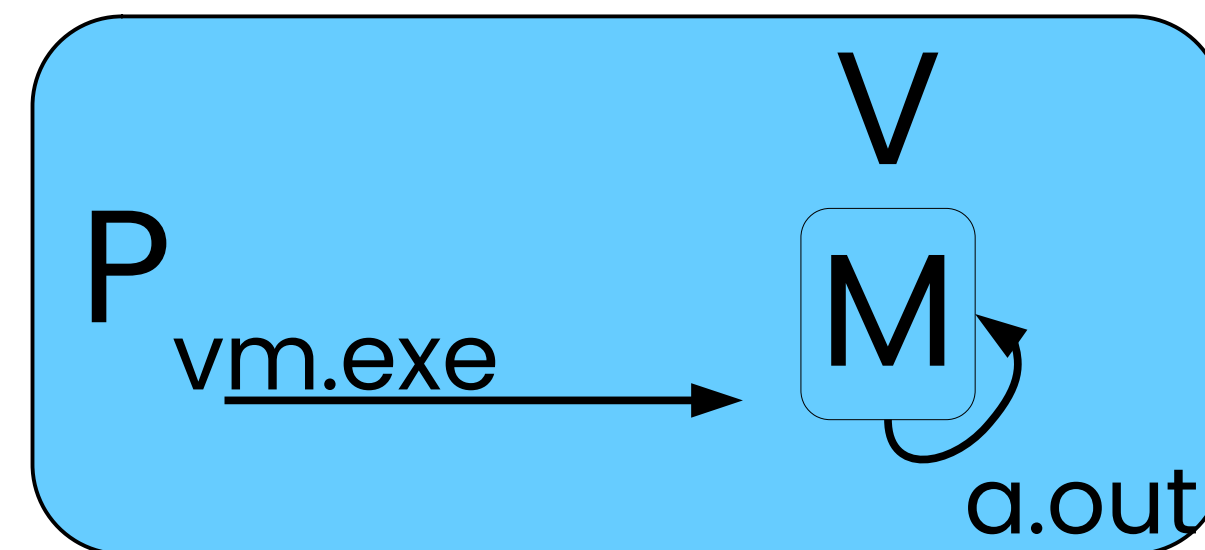


Compile: $vm.cc \rightarrow gcc \rightarrow vm.exe$ **Run**: $vm.exe \rightarrow \text{answer}$

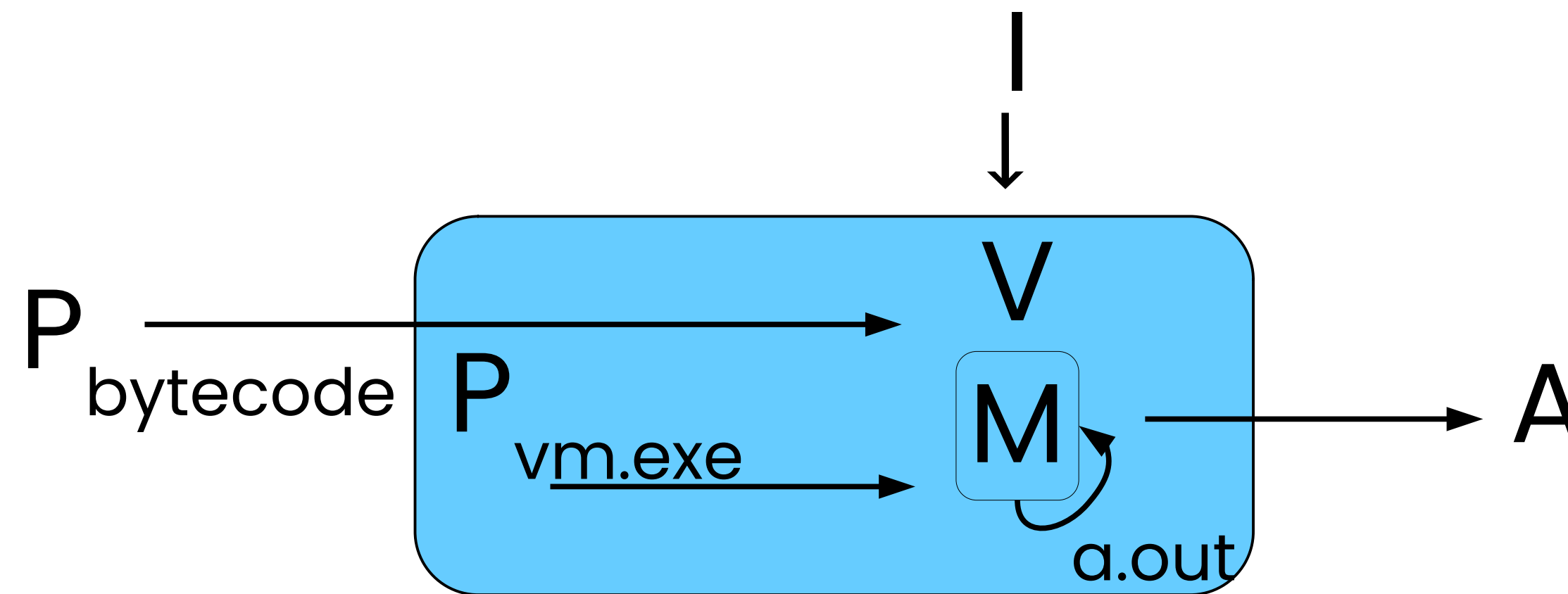
A Virtual Machine is a Program



The Real Machine runs a Program that
lets it mimic a Virtual Machine,
often one that's hard to build physically.



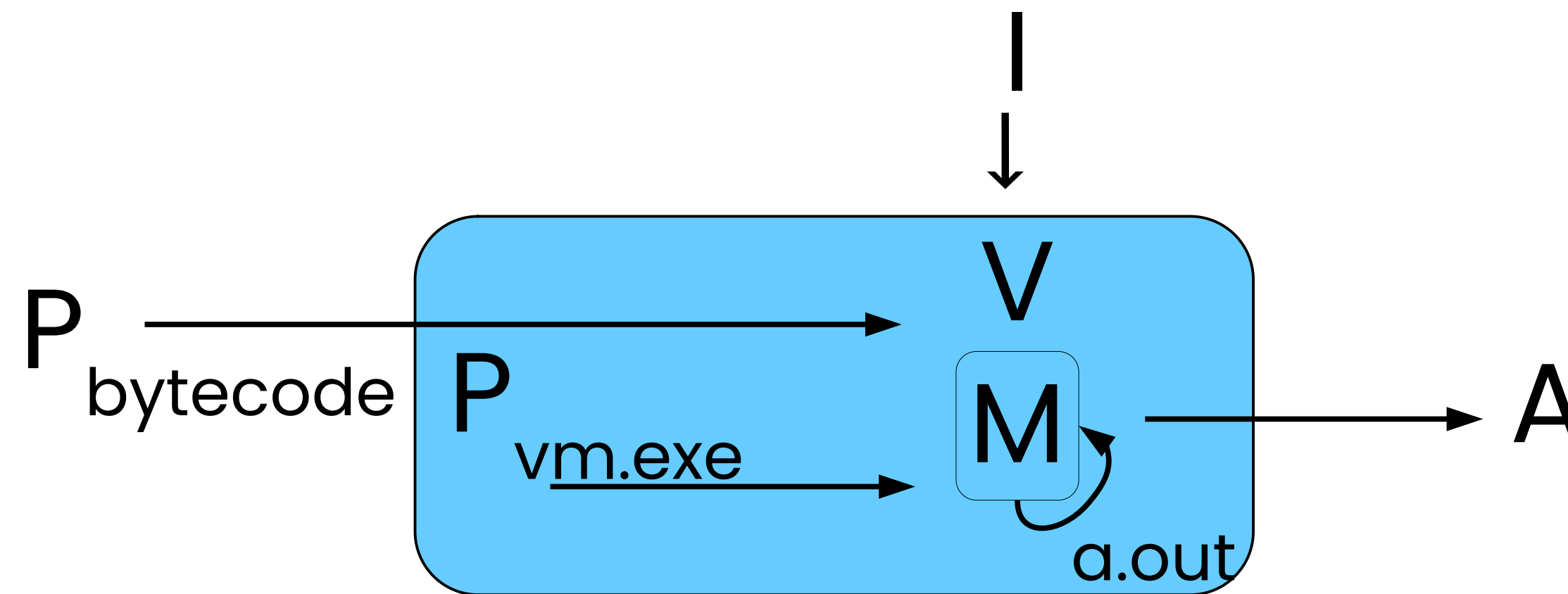
The Virtual Machine runs a virtual machine code, often called “bytecodes”, but otherwise mimics a Real Machine.



Ex: Java Virtual Machine, JavaScript, Python

But also: Vmware, hyper-V, virtual box

Any program running “in a sandbox”



A (Virtual) Machine

Acts like a Real Machine:

- Reads a “recipe”, produces an “answer”

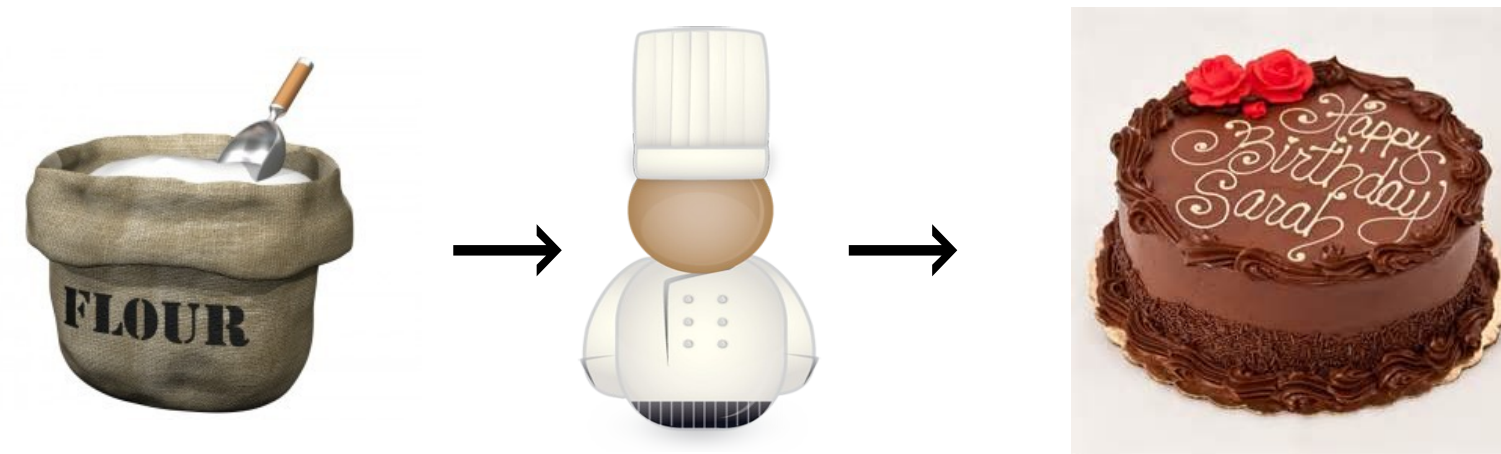
But it's Virtual not Real

Because it does things no Real Machine can do!

- Supports GC, Or Type-Safe Execution, Or
- Switches OS's and Containers and Dockers
- Most hypervisors “nearly perfectly” mimic the Real Machine

The tradeoff is usually Time

Not all Programs are created equal.
Programs follow rules, but often
the rules do not mention Time.



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the rules do not mention Time.

Faster programs are usually better.

Same Program, same Answer, but Faster



Still Can't Fool Time

Although you can get really close

Ultimately, the emulated program can tell if there is any tiny deviation from the Real Machine

Often there are Giant time deviations

- Reading hardware registers
- Doing “cheap” OS calls
- Looking at extern things, e.g. file timestamps

The Illusion is never Perfect

- Specter and Meltdown exactly show this

And Time is At the Heart...

Time weaves through all we do

- Some VMs are **faster** to program
- Some VMs allow sharing a resource instead of **waiting**
- Some VMs exist solely to run a **no-longer-existing** Machine

Designing A Virtual Machine

VMs are Big Complex Beasties

- Really Really Small (e.g., Squawk, OOVm)

Depends on the Feature Set

- Easily 4 orders of magnitude in effort

Many features interact in Bad Ways

- Usually interactions not obvious

I went the Big Desktop/Server route

- Very different choices from the cell-phone guys
- Must solve a different set of problems

I suspect most of this applies to .Net, JS as well



Designing A Virtual Machine

Real Hardware & OS

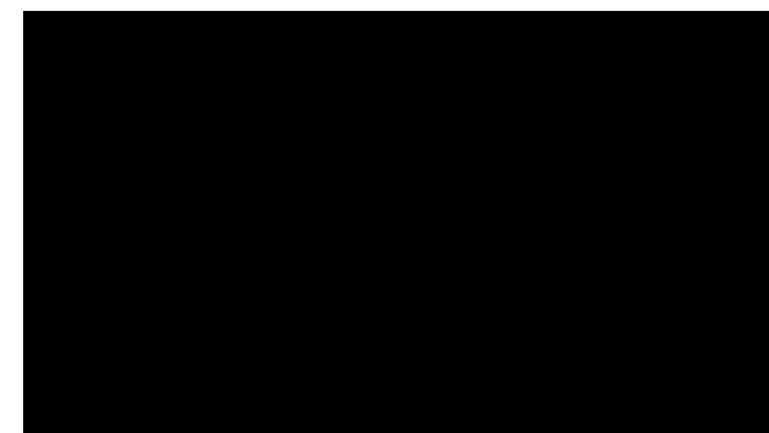
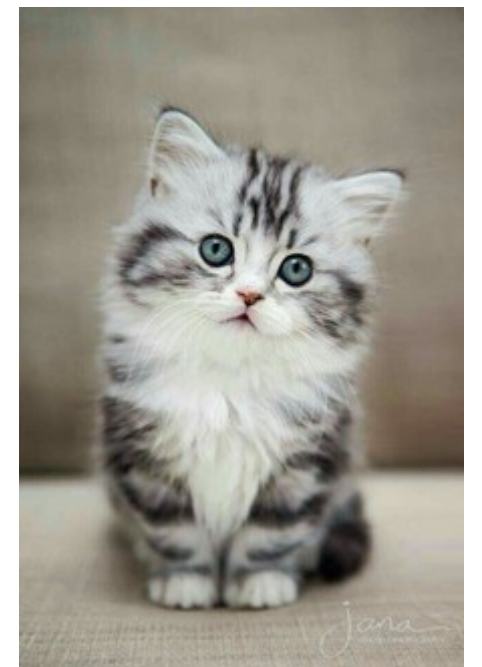
- Servers-vs-Cell-phone-vs-embedded (Footprint!)
- Portable or Single-Target, Endianess, Calling ABI

Language Support

- GC, Memory Models, Threading
- Basic object model, basic Math model

Speed and Power

- JIT'ing, Threading



Interpreter Choices

Simple, software only

- Pure C
- GCC label vars (about 2x faster than pure C)
- Pure ASM (about 2x faster again)

Hardware support (ARM jazelle, pico-Java, Azul?)

Fancy: inline & schedule dispatch

- Seen at least 2 different ways to slice this

Requires stack oriented layout, bad for JITs

or none at all...



Some JIT Choices

“Just In Time” Compilation

- None? (gives up peak performance)
- stage0, template style?
- stage1, light optimization, linear-scan allocator?
- stage2, all the optimizations, graph-coloring?

Portable or targeted (usual X86 + Vendor)?

Intercalls with native?

- Messes with calling convention

Support fancy JIT + Deopt?



More JIT Choices

Stage-0 JIT + No Interpreter

Template generation, very fast low quality code

No funny stack layouts

- Easy calling conventions for all

Still slower than just interpreting run-once code

- Lots of run-once code at startup
- Lots of bulky code to startup
- Big footprint
- Can throw away & regenerate



GC Choices

GC – Yes/No?

- Simple? (single generation, StopTheWorld?)
- Fast? (Throughput? Low pause?)
- Exact? (moving objects, compaction, de-frag, bump pointer alloc)
- Conservative? (No need to track all objects)
- Tried & true? (e.g. Mark/Sweep)
- Fancy new algorithm?

Parallel? (really hard!)

Concurrent? (really really hard!)

Both? (really⁴ hard!)



More GC Choices

Stop-Anywhere

- OOP Maps at each PC? (bulky data)
- Interpret instructions? (hard/slow on X86)
- Fixed OOP registers & stack areas? (bad register usage)
- Conservative-on-stack, exact-on-heap?

Safepoints

- Cooperative? (polling costs?)
 - Polling in software vs hardware?
- Preempt at wrong place?
- Roll forward vs step forward vs interpret?



Threading

Multi-threading costs

- All operations no longer **atomic**
- May be preempted inconveniently
- Need locking (never needed it before!)

Threads can block for I/O, or deadlock

GC requires SP & PC for stack roots

- Hard to find the SP & PC of remote thread
- Common problem of OS's

! **Very** surprising to me, until I tried it !

Fails (w/low frequency) on many “robust” OSes!

Caught in page fault handler,
nested in tlb handler,
nested in stack overflow handler
nested in



Multi-Core

Multi-Cores?

- Now need **Atomic** operations
- Coherency, memory fences, a Memory Model
- Low-frequency **data race bugs**

Need *scale-able* locks in VM & JIT'd code

- Not just correctness locks
- Spinning & retries
- '**fair**' locks under super high contention

GC can be in-progress when a thread awakens

- Threads now need to take a form of GC lock to run



What Is A VM?

It can be A whole lot! Or maybe just a Little

The **V** in **Virtual** is a **powerful** abstraction

Used by Billions of Programs & Millions of Programmers every day

I've really enjoyed writing VMs

I hope you get the chance to write one too!

