The Scientific Method

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A Sample Program

```
$ sample 9 8 7
Output: 7 8 9

$ sample 11 14
Output: 0 11
```

Where's the *error* that *causes* this failure?

Errors

What's the error in the sample program?

- An *error* is a deviation from what's correct, right, or true. (IEEE glossary)

To prove that something is an error, we must *show the deviation:*

- *Simple* for failures, *hard* for the program

Where does sample.c deviate from – what?

Causes and Effects

What's the cause of the sample failure?

- The *cause* of any event (”effect”) is a preceding event without which the effect would not have occurred.

To prove causality, one must show that

- the effect occurs when the cause occurs
- the effect does *not* occur when the cause does not.

Establishing Causality

In natural and social sciences, causality is often hard to establish.

- Did long lines at election sites cause George W. Bush to become president?
- Did drugs cause the death of Elvis?
- Does CO_2 production cause global warming?

Repeating History

- To determine causes formally, we would have to *repeat history* – in an alternate world that is as close as possible to ours.
- Since we cannot repeat history, we have to *speculate* what *would* have happened.
- Some researchers have suggested to drop the concept of causality altogether

Repeating Runs

In computer science, we are luckier:

- Program runs can be controlled and repeated at will
  (well, almost: physics can't be repeated)
- Abstraction is kept to a minimum – the program is the real thing.

“Here’s the Bug”

- Some people are good at guessing causes!
- Unfortunately, intuition is hard to grasp:
  - Requires *a priori knowledge*
  - Does not work in a systematic and reproducible fashion
  - In short: *Intuition cannot be taught*

The Scientific Method

- The *scientific method* is a general pattern of how to find a *theory* that explains (and predicts) some aspect of the universe
- Called "scientific method" because it's supposed to summarize the way that (experimental) scientists work

The Scientific Method

1. Observe some aspect of the universe.
2. Invent a *hypothesis* that is consistent with the observation.
3. Use the hypothesis to make *predictions*.
4. Tests the predictions by experiments or observations and modify the hypothesis.
5. Repeat 3 and 4 to refine the hypothesis.

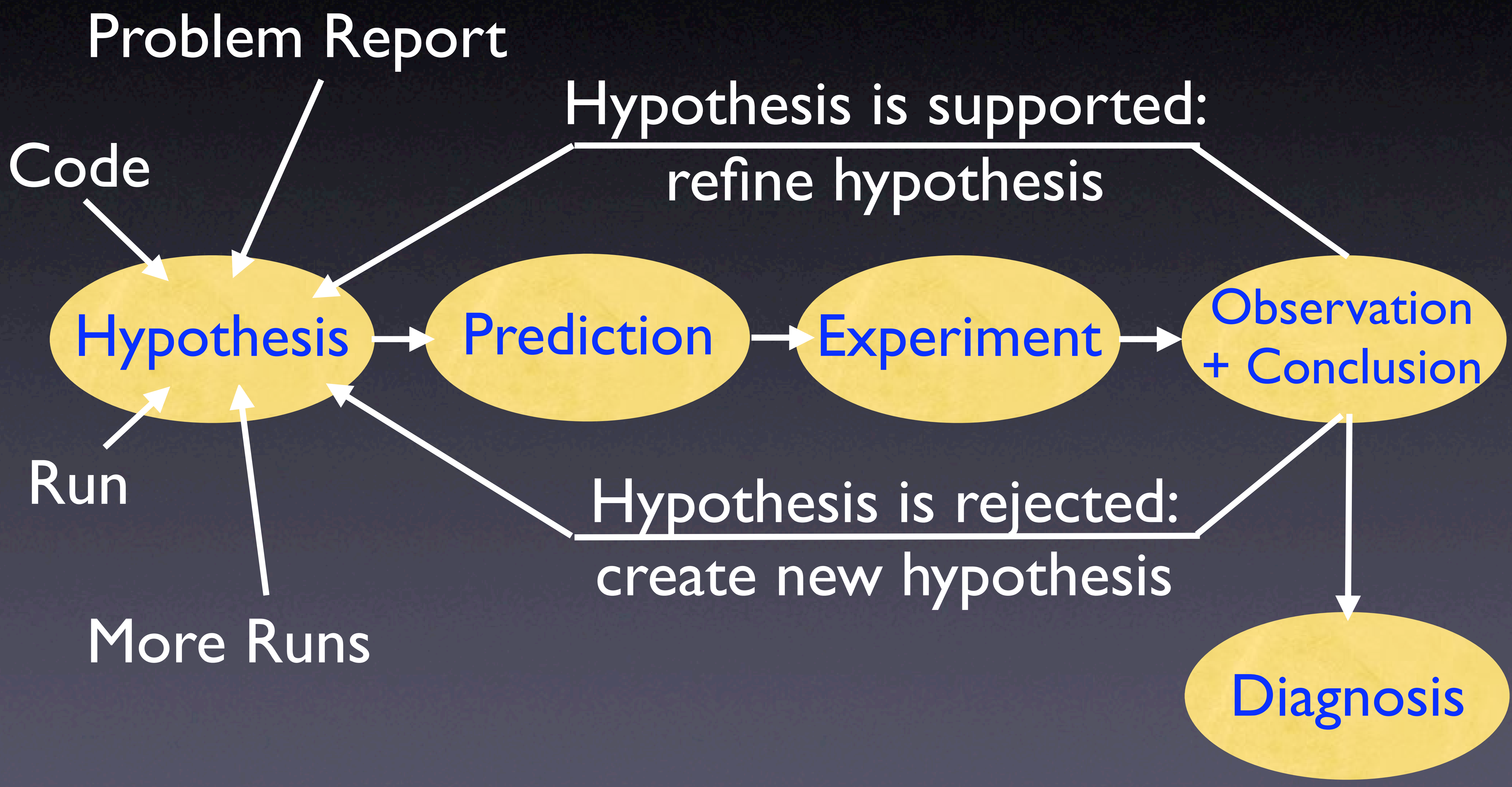
A Theory

- When the hypothesis explains all experiments and observations, the hypothesis becomes a *theory*.
- A theory is a hypothesis that
  - explains earlier observations
  - predicts further observations
- In our context, a theory is called a *diagnosis*
  (Contrast to popular usage, where a theory is a vague guess)

Mastermind

- A Mastermind game is a typical example of applying the scientific method.
- Create hypotheses until the theory predicts the secret.

Scientific Method of Debugging



A Sample Program

```
$ sample 9 8 7
Output: 7 8 9

$ sample 11 14
Output: 0 11
```

Let’s use the scientific method to debug this.

Initial Hypothesis

Hypothesis	"sample 11 14" works.
Prediction	Output is "11 14"
Experiment	Run sample as above.
Observation	Output is "0 11"
Conclusion	Hypothesis is **rejected**.

```
int main(int argc, char *argv[])
{
    int *a;
    int i;

    a = (int *)malloc((argc - 1) * sizeof(int));
    for (i = 0; i < argc - 1; i++)
        a[i] = atoi(argv[i + 1]);

    shell_sort(a, argc);

    printf("Output: ");
    for (i = 0; i < argc - 1; i++)
        printf("%d ", a[i]);
    printf("\n");

    free(a);

    return 0;
}
```

Does a[0] = 0 hold?

Hypothesis 1: a[]

Hypothesis	The execution causes a[0] = 0
Prediction	At Line 37, a[0] = 0 should hold.
Experiment	Observe a[0] at Line 37.
Observation	a[0] = 0 holds as predicted.
Conclusion	Hypothesis is **confirmed**.

```
static void shell_sort(int a[], int size)
{
    int i, j;
    int h = 1;
    do {
        h = h * 3 + 1;
    } while (h <= size);
    do {
        h /= 3;
        for (i = h; i < size; i++)
        {
            int v = a[i];
            for (j = i; j >= h && a[j - h] > v; j -= h)
                a[j] = a[j - h];
            if (i != j)
                a[j] = v;
        }
    } while (h != 1);
}
```

Is the state sane here?

Hypothesis 2: shell_sort()

Hypothesis	The infection does not take place until shell_sort.
Prediction	At Line 6, a[] = [11, 14]; size = 2
Experiment	Observe a[] and size at Line 6.
Observation	a[] = [11, 14, 0]; size = 3.
Conclusion	Hypothesis is **rejected**.

Hypothesis 3: size

Hypothesis	size = 3 causes the failure.
Prediction	Changing size to 2 should make the output correct.
Experiment	Set size = 2 using a debugger.
Observation	As predicted.
Conclusion	Hypothesis is **confirmed**.

Fixing the Program

```
int main(int argc, char *argv[])
{
    int *a;
    int i;

    a = (int *)malloc((argc - 1) * sizeof(int));
    for (i = 0; i < argc - 1; i++)
        a[i] = atoi(argv[i + 1]);

    shell_sort(a, argc); 1);

    ...
}
```

```
$ sample 11 14
Output: 11 14
```

Hypothesis 4: argc

Hypothesis	Invocation of shell_sort with size = argc causes the failure.
Prediction	Changing argc to argc - 1 should make the run successful.
Experiment	Change argc to argc - 1 and recompile.
Observation	As predicted.
Conclusion	Hypothesis is **confirmed**.

The Diagnosis

- Cause is "Invoking shell_sort() with argc"
- Proven by two experiments:
  - Invoked with argc, the failure occurs;
  - Invoked with argc - 1, it does not.
- Side-effect: we have a *fix*
  (Note that we don't have *correctness* – but take my word)

Explicit Debugging

- Being explicit is important to understand the problem.
- Just *stating* the problem can already solve it.

Keeping Track

- In a Mastermind game, *all* hypotheses and observations are explicit.
- Makes playing the game much easier.

Implicit Debugging

- Remember your last debugging session: Did you write down hypotheses and observations?
- Not being explicit forces you to keep all hypotheses and outcomes *in memory*
- Like playing Mastermind in memory

Daysleeper

I'm the screen, the blinding light
I'm the screen, I work at night

I see today with a newsprint fray
My night is colored headache grey
Don't wake me with so much
Daysleeper

Keep a Notebook

Everything gets written down, formally, so that you know at all times

- where you are,
- where you've been,
- where you're going, and
- where you want to get.

Otherwise the problems get so complex you get lost in them.

What to Keep

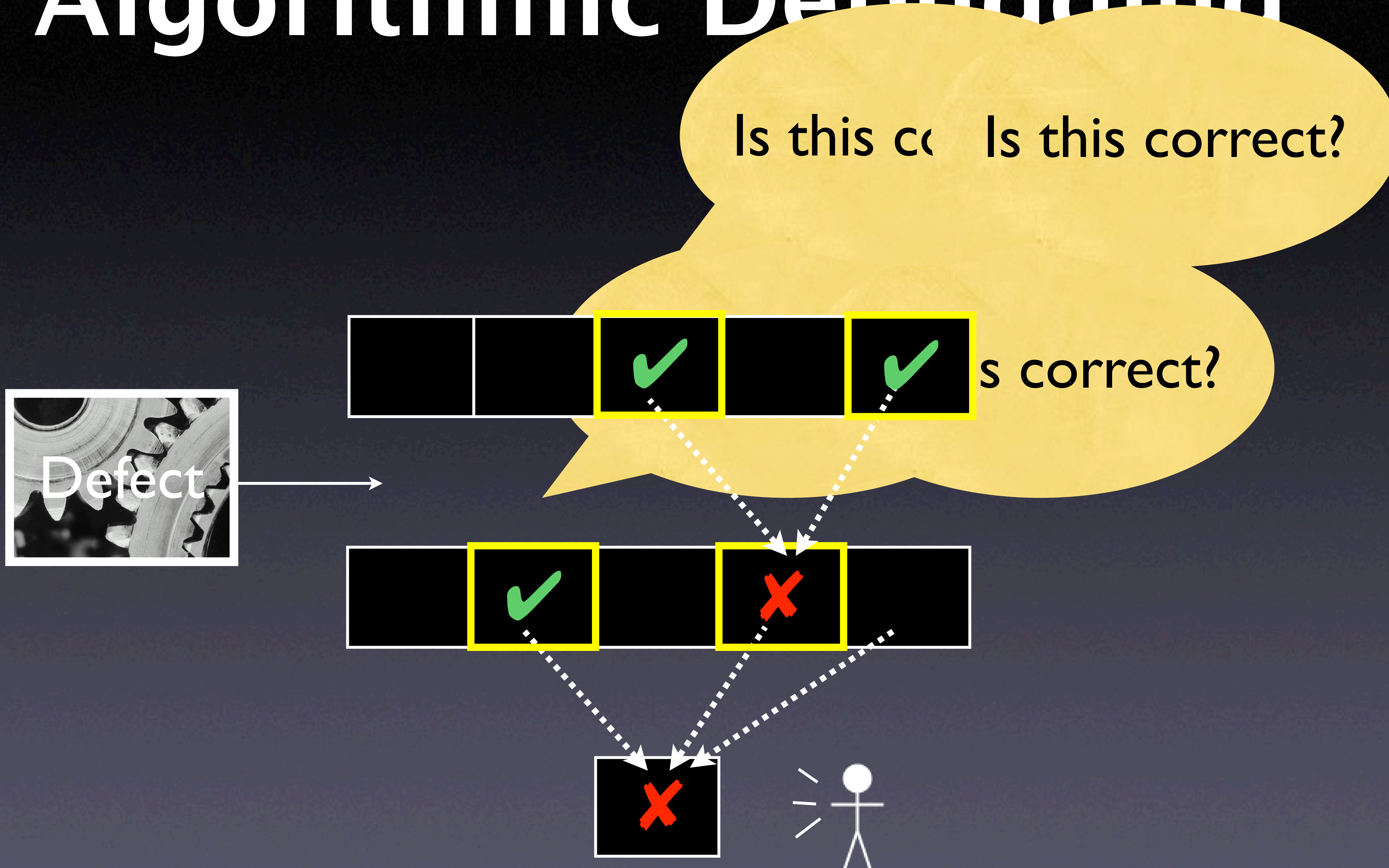
Hypothesis	
Prediction	
Experiment	
Observation	
Conclusion	

Faced with a difficult task,
"sleeping on it" makes students
three times more apt
to solve the task the next morning.

Quick and Dirty

- Not every problem needs the strength of the scientific method or a notebook – a quick-and-dirty process suffices.
- Suggestion: Go quick and dirty for 10 minutes, and then apply the scientific method.

Algorithmic Debugging

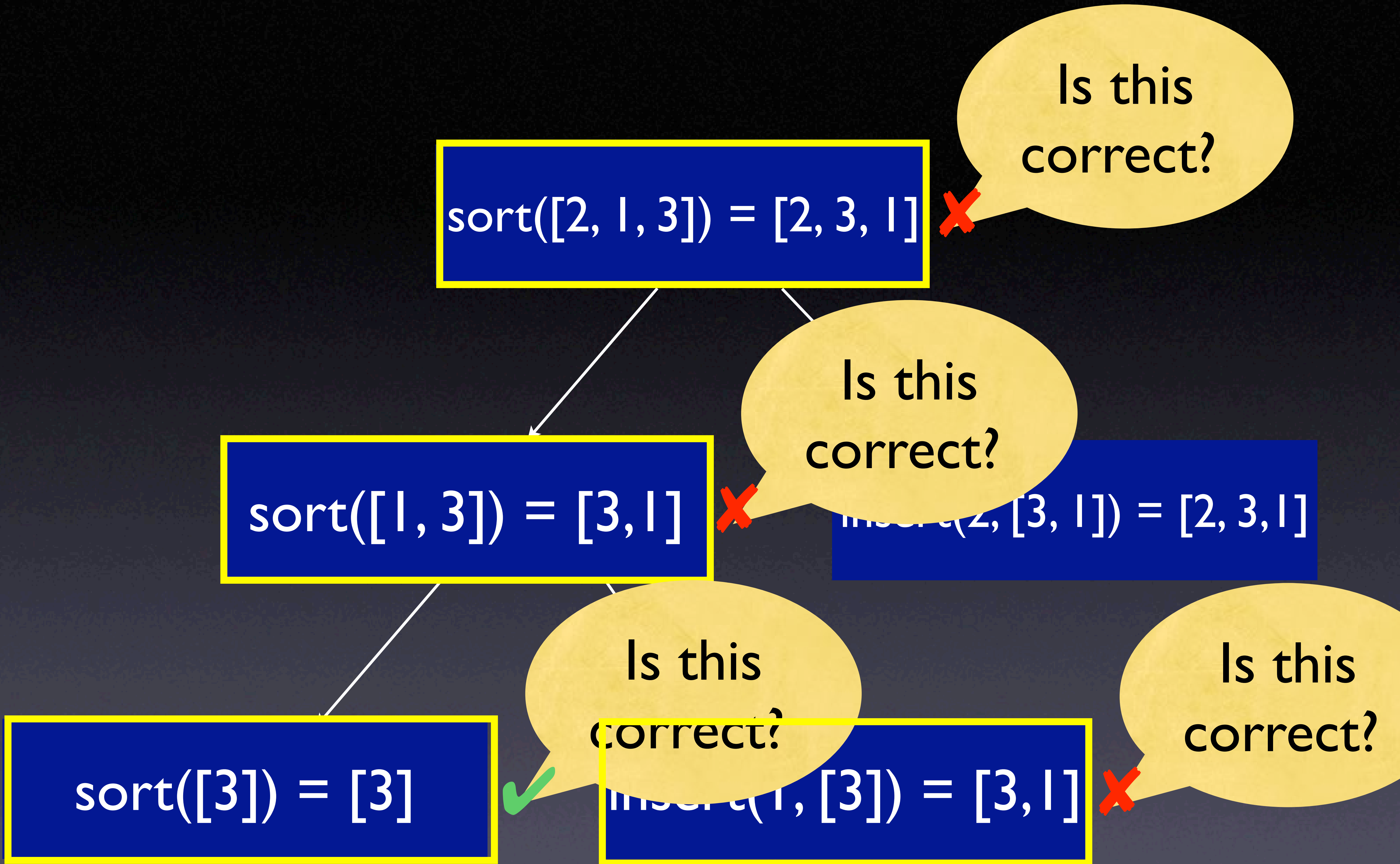


Algorithmic Debugging

1. Assume an incorrect result R with origins $O_1, O_2, \ldots, O_n$
2. For each O_i, enquire whether O_i is correct
3. If some O_i is incorrect, continue at Step 1
4. Otherwise (all O_i are correct), we found the defect

```python
def insert(elem, list):
    if len(list) == 0:
        return [elem]
    head = list[0]
    tail = list[1:]
    if elem <= head:
        return list + [elem]
    return [head] + insert(elem, tail)


def sort(list):
    if len(list) <= 1:
        return list
    head = list[0]
    tail = list[1:]
    return insert(head, sort(tail))
```


sort([2, 1, 3]) = [2, 3, 1]
Is this correct?
sort([1, 3]) = [3,1]
Is this correct?
[3, 1]) = [2, 3,1]
sort([3]) = [3]
Is this correct?
[3]) = [3,1]
Is this correct?

Defect Location

- insert() produces an incorrect result and has no further origins:
- It must be the source of the incorrect value

insert(1, [3]) = [3,1] ✘

```python
def insert(elem, list):
    if len(list) == 0:
        return [elem]
    head = list[0]
    tail = list[1:]
    if elem <= head:
        return list + [elem]
    return [head] + insert(elem, tail)


def sort(list):
    if len(list) <= 1:
        return list
    head = list[0]
    tail = list[1:]
    return insert(head, sort(tail))
```

[elem] + list

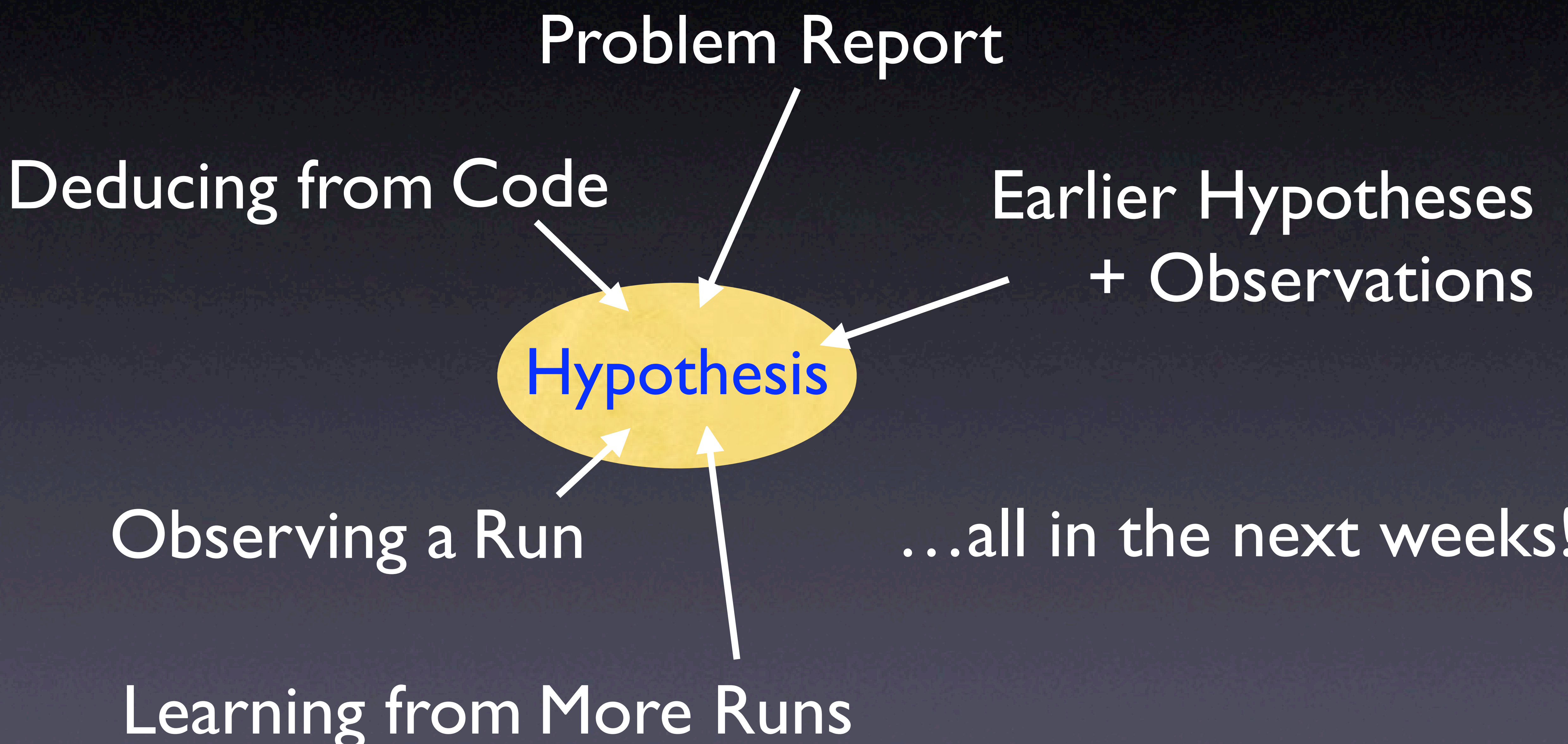
Discussion

- ✔ Detects defects systematically
- ✔ Works naturally for logical + functional computations
- ✘ Won’t work for large states (and imperative computations)
- ✘ Do programmers like being driven?

Oracles

- In algorithmic debugging, the user acts as an *oracle* – telling correct from false results
- With an *automatic oracle* could isolate any defect automatically.
- How complex would such an oracle be?

Obtaining a Hypothesis



Sources of Hypotheses

Experimentation	*n* controlled runs
↓ Induction	*n* runs
↓ Observation	1 run
↓ Deduction	0 runs

Concepts

- A *cause* of any event ("effect") is a preceding event without which the effect would not have occurred.
- To isolate a failure cause, use the *scientific method.*
- Make the problem and its solution *explicit.*

Concepts

- Automated debugging organizes the scientific method by having the user assess outcomes
- Best suited for functional and logical programs