

# Best Practices *of* Spell Design

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A COMPUTATIONAL FAIRY TALE

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```

IF ((time < 1 day) OR ((time < 1 week) AND (workers
< 5)) OR ((time < 2 hours) AND (workers < 2))):
    IF ((time < 2 hours) AND (workers < 2)):
        IF (the work needs power tools):
            prohibit the work
        ELSE:
            allow the work
    ELSE:
        IF (the work needs power tools):
            prohibit the work
        ELSE:
            allow the work in 4-hour shifts
ELSE:
    IF (the work needs power tools):
        prohibit work
    ELSE:
        consult with steward

```

“First, the organization of the initial Boolean statement makes it difficult to read. The condition consists of three separate clauses that are ORed together. However, that structure is not at all apparent. It would be clearer if you broke up the lines to match the expressions.”

The steward wrote an expression on the blank parchment:

```

IF ((time < 1 day) OR
(time < 1 week) AND (workers < 5)) OR
((time < 2 hours) AND (workers < 2))):

```

“And, in this case, you could further improve the readability by removing the constituent Boolean clauses and capturing them in well-named variables.”

```

is_small_job = (time < 2 hours) AND (workers < 2)
is_medium_job = ((time < 1 week) AND (workers < 5))
OR (time < 1 day)
if (is_small_job or is_medium_job):

```

“Next, consider the organization of the rules. Regardless of job size, we prohibit work that requires power tools. You can therefore combine several IF tests by bringing this condition to the top.”

```
is_small_job = (time < 2 hours) AND (workers < 2)
is_medium_job = ((time < 1 week) AND (workers < 5))
OR (time < 1 day)
IF (the work does not need power tools):
    IF (is_small_job):
        allow the work
    ELSE IF (is_medium_job):
        allow the work in 4-hour shifts
    ELSE:
        consult with steward
ELSE:
    prohibit work
```

As he wrote, he added, "I cannot emphasize enough the risk now posed by a simple drill. It is imperative that we adhere to the 'no power tools' condition. These rules must be absolutely clear."

Once the steward finished writing the new conditions, he looked up. "Have you any questions?"

The scribe studied the parchment for a minute, forcing himself not to comment on the steward's handwriting. The letters were well formed, but too linear and cold. Even the o's didn't seem round enough.

"What I have is correct, though. Isn't it?" asked the scribe.

"It is correct, although it was difficult to confirm that fact," the steward said. "More importantly, it would be difficult for most of the castle vendors to follow it correctly. Remember, readability is not just about handwriting."

He handed both the draft rules and his notes to the scribe.

"Please clean up the conditions and bring the regulations back within the hour," the steward concluded in his usual polite tone. "We have no time to waste in implementing these new policies."

Then he forced a pleasant smile, waved the scribe out, and turned back to his own stacks of paperwork.

## Functions

Three days later, Shelly found Marcus hunched over Hannaldous's scroll. He sat, head in his hands, mumbling to himself. Panic coursed through her. A mumbling wizard was never a good sign.

"Are you okay?" Shelly asked.

Marcus looked up at her, his eyes bloodshot. He had been working on the scroll nonstop but had made little progress.

"Functions," Marcus croaked. Then clearing his throat, "Hundreds of pages of spells with only one function."

"Functions?" asked Shelly. She had heard the term before but hadn't reached it in her own training. She silently cursed Marcus's excruciatingly thorough teaching style.

"Subspells, if you prefer," explained Marcus, "Functions are separate blocks of instructions that can be reused throughout a complex spell. Each function has a single, well-defined goal—one thing that it does. And it has clear inputs and outputs.

"Remember the Spell of Glowing Ants?" asked Marcus. "It had a function called `IncreaseLuminosityOfSurface`."

He rummaged through a desk drawer until he found the spell.

"Here's the function," he noted, pointing to a section of instructions.

```
IncreaseLuminosityOfSurface (surface) :
```

```
    make two small wand loops in the air
    point wand at surface
    clearly state "get ye brighter"
    flick wand one time at surface
```

"Admittedly, it's a simple function. But we called it at least a dozen times." He pointed to a few blocks of instructions further down in the spell:

```
FOR each leg:
```

```
    IncreaseLuminosityOfSurface (leg)
```

and then, on the next page:

```
WHILE (ant is not bright enough) :
```

```
    IncreaseLuminosityOfSurface (thorax)
    measure the brightness
```

"It's the same instructions each time, so we can break it out into a function. The only part that changes is the input," said Marcus. "Imagine if we had to write out the instructions separately for each leg and the thorax."

Shelly thought for a while as she studied the spell. "Functions make the spell more compact by removing repeated lines?" she ventured, remembering her recent discussion with Ivan about subrecipes.

“That’s one benefit,” Marcus agreed. “Functions also make the spell more readable and reduce errors. You improve readability by replacing a chunk of spell with a single, well-named function. You reduce errors by having one implementation, which you can thoroughly test.”

Marcus turned back to Hannaldous’s scroll and waved around seemingly at random. “Do you see these eight blocks I circled in red?” he asked.

Shelly nodded. The circles were hard to miss; she had been conditioned to notice them. A feeling of angst welled up inside her as she flashed back to her own previous assignments, parchments soggy with red ink. She turned aside, clenching her eyes shut, and took a few deep breaths. “This is not my assignment,” she reminded herself in the faintest whisper.

Marcus didn’t notice the reaction.

“Eight blocks of instructions doing the exact same thing!” Marcus scoffed. “Each one clears a surface of insects. This one clears the castle rocks. This one clears the ground within an inch of the castle walls. This one clears a sandwich—why would he need that one?” Marcus trailed off with a worried look on his face.

After a moment he shrugged and continued, “Anyway, they all do the same thing. Or, at least, they’re supposed to. The one to clear his sandwich has a small mistake and won’t work on beetles.

“Imagine how much simpler this scroll would look if Hannaldous had used a function,” Marcus continued. “And, if he had tested it, he would have ensured that his sandwich stayed beetle-free.”

He copied Hannaldous’s instructions into a `ClearBugsFromSurface` function on a clean piece of parchment.

“After he wrote out the instructions once as a separate function, he could then call `ClearBugsFromSurface(walls)` to replace these 50 lines on page 63,” said Marcus, pointing to the corresponding block of instructions. “And `ClearBugsFromSurface(ground)` could replace the instructions on pages 103, 105, and 106.”

Suddenly the concept clicked into place in Shelly’s brain.

“It’s like a guitar!” exclaimed Shelly.

“What?” asked Marcus with a look of annoyance. “How is it anything like a guitar?”

“Each chord is a function,” explained Shelly, “Any chord, say, B-minor for example, requires the correct finger positions and strum pattern. You need to execute multiple motions, but they’re all represented by two letters in the sheet music. You learn a few functions, one for each chord, and apply them repeatedly throughout every song.”

“I suppose that’s true,” agreed Marcus.

“Or cooking,” continued Shelly, beaming with excitement. “I bet lots of recipes say ‘Make fifty pounds of pastry dough,’ but that’s just a function. Making dough is a set of instructions itself. It has input ingredients. You use flour, right? It even has an output.”

“Or—”

“Yes, yes,” interrupted Marcus. “Functions are everywhere, except in this scroll. If only Hannaldous had possessed your excitement for functions, interpreting this mess would be easier.”

As Marcus shifted his attention back to the scroll, Shelly lingered behind him.

“Umm ...” she started.

Marcus looked back up.

“What should I do today?” she asked.

Marcus glanced around the room as though looking for inspiration.

“I suppose today is as good a day as any for you to learn functions,” he said. “Copy down this function for removing bugs from surfaces. Test it on the cellar floor. Then incorporate it into a general cellar-cleaning spell.”

Shelly’s nose wrinkled in disgust, but she said nothing. The bugs in the cellar creeped her out almost as much as they did Marcus. She knew a punishment when she heard one. As she left to begin her lesson for the day, she resolved to be less exuberant when Marcus was working.

## Testing Software

The steward strode purposefully around the castle's perimeter. His choppy gait propelled him efficiently along the stone path. For anyone else, this excursion would have been a stroll—a chance to walk and think. The steward, however, did not stroll.

As he walked, he replayed the conversation with Hannaldous in his head. A few days before Hannaldous had accidentally cursed the castle, they had met to discuss the final details.

“How are you going to test the spell?” the steward had asked.

Hannaldous's scoff had surprised him. “Wizards never test their spells. It's a waste of time, and our time is valuable.”

“I believe testing is a standard practice in the wizarding community,” argued the steward. “What of the story of Bianca and the Spell of Moderate Rainfall? It is said that her initial version contained an error in the timing control; a constant was off by a factor of ten. However, she discovered the error by testing the spell on a small patch of land where the Peatbody Swamp is today.”

Hannaldous laughed. “Bianca was a junior wizard then, and that was her first major work. She probably had nothing better to do than write a test.”

“Surely you should practice this spell on something small first,” said the steward. “Why not the royal chicken coop? I am quite certain the chickens would not mind. By now they should have forgotten about the carpenter's last experiment.”

Of course, Hannaldous had not been swayed. Wizards were notoriously stubborn.

Now the steward chastised himself for not pushing harder. Launching an untested spell was reckless; even the steward knew that. Every child in the kingdom had grown up to the tales of Fantastic Freddy, and every child had heard about the untested Spell of Healthy Produce.

Meant to help the farmland, the Spell of Healthy Produce had been a disaster. The town of Asherton had seen unimaginable destruction as giant plants tore out of the ground. Asparagus shoots destroyed houses, punching through the foundations and shattering the roofs. The town had finally been abandoned after an eighty-foot pumpkin broke free, flattening three buildings before impaling itself on the corner of city hall with a deafening *splack*. It's said that a two-hundred-foot cornstalk towers over the town to this day.

Muttering to himself, the steward continued his walk.

A curious sight stopped the steward in his tracks and forced his mind back to the present. A smattering of colorful mushrooms dotted the base of the castle's wall. Although they were likely poisonous, the steward had to admit that their bright purple caps added a bit of style to the otherwise grey walls.



The steward glanced around until he found a suitably long stick. Then, with impressive precision, he began knocking mushrooms off the wall. The castle walls were no place for style. Grey was traditional. Grey was impressive.

“Wizards are too busy to test spells,” he muttered under his breath as he worked.

His swings came harder and faster. Mushroom caps fell from the walls, forming a beautiful pile in the short grass. The steward made a mental note to send someone to dispose of the pile before the royal pets found it. The pets displayed a consistent lack of common sense when it came to eating random items. Most recently, the king’s hedgehog had amazed everyone by consuming nearly a pound of construction gravel.

After a few minutes, the wall was mostly clear of purple fungi. The steward stepped back to survey the work. He knocked away the three surviving mushrooms and nodded with satisfaction.

Then the steward saw the rabbits, and he screamed.

## Designing Spells

For the second time in three days, Marcus traveled to the capital to meet with the steward. This time, he brought along Shelly, hoping to use the audience as a teaching opportunity.

The steward relayed the latest developments with a barely detectable note of panic. He kept his face impassive and his voice formal, but his eyes betrayed him. Marcus thought that the poor man looked rather stressed.

Purple mushrooms weren't a good sign, but they weren't necessarily a bad sign either. Oddly colored fungi were a common byproduct of sloppy magic. Marcus's own garden held numerous examples—mostly in bright shades of green. One patch of particularly vivid topaz mushrooms served as a reminder not to cast spells before his first cup of coffee.

The rabbits, however, were a problem. Technically, they had nothing to do with the spell itself. They were simply opportunistic. Once they had realized that they could dig into the soft stone, they had set about burrowing. Left unchecked, they would eventually wind tunnels throughout the entire outer wall.

"I suggest hawks," Marcus said.

"Hawks?" asked the steward. "Why not a magical solution? Surely there must be something you can do."

Marcus shook his head. "The castle's condition is too fragile, and I still don't know the depth of Hannaldous's spell. I wouldn't risk adding more magic. Further, the rabbits may have interacted with the magic. They've been burrowing in cursed stone, after all. That can't be good for them. For all I know, a vanishing spell might give them fangs."

The steward's eyes widened in shock.

"In the meantime," Marcus continued, "the rabbits are weakening the walls. Hawks should scare them away and buy us some more time. You can use another bird of prey if you prefer. I don't have any strong feelings there. Hawks were just the first bird that came to mind, after sparrows—but I don't expect sparrows will be much help in scaring away rabbits."

The steward gave a stiff nod. "I shall see to it at once. On the matter of time, how is your progress on the reverse spell?"

Shelly, who had been standing quietly to the side, looked up. She had spent the last two days listening to nonstop complaints about Hannaldous's spell. Marcus could see her brace for another diatribe, which annoyed him further.

"Not well, I'm afraid," said Marcus. "I'm having difficulty deciphering the original spell. It appears Hannaldous never learned to design spells correctly."

For the briefest instant, the steward looked uncertain. "Despite this most recent incident, I believe that Hannaldous has successfully designed

many spells in the past,” he said. It obviously pained him to defend Hannaldous.

“He wrote spells,” Marcus agreed. “But there’s a difference between writing a spell down and designing a spell.

Again the steward pushed, “But surely there must have been some design. The spell is hundreds of pages in length. It’s incredibly complex.”

“The problem does require a complex spell, but nothing nearly this complex,” Marcus explained. “In this case, the spell’s length is another symptom of poor design. The number of instructions shouldn’t be confused with the spell’s quality. Whenever possible, you should prefer simplicity and avoid unnecessary complexity. I’ve seen five-line spells so beautiful they almost made me cry. This spell makes me cry for completely different reasons.

“The basic point, though,” Marcus continued, “is that a complex spell needs structure. It needs to be designed.

“Think about a birdhouse,” Marcus suggested. “The best architects will spend months drawing out careful blueprints before the carpenters cut the first piece of wood. They have to design the birdhouse—create a structure to work from. Otherwise, you end up with another royal chicken coop mistake. And it’s a lot more work to patch up bad designs after the fact, plus the end result is never as high quality.”

“I’ve seen you write spells without designing them,” said Shelly. She immediately clapped her hands to her mouth and turned bright red.

Marcus turned toward his apprentice. He took a deep breath, stifled the urge to yell at her, and smiled.

“It depends on the size and complexity of the spell,” Marcus said. “It’s true that I don’t spend much time designing small spells. I can write a ten-line spell from start to finish without worrying about structure. I can often cast a five-line spell without even writing it down.

“But, for larger spells, I design them first. I might even prototype a few different approaches. A fast prototype can provide invaluable insight into the problem.

“And for something this large,” Marcus gestured to the castle all around them. “You need multiple levels of design.”

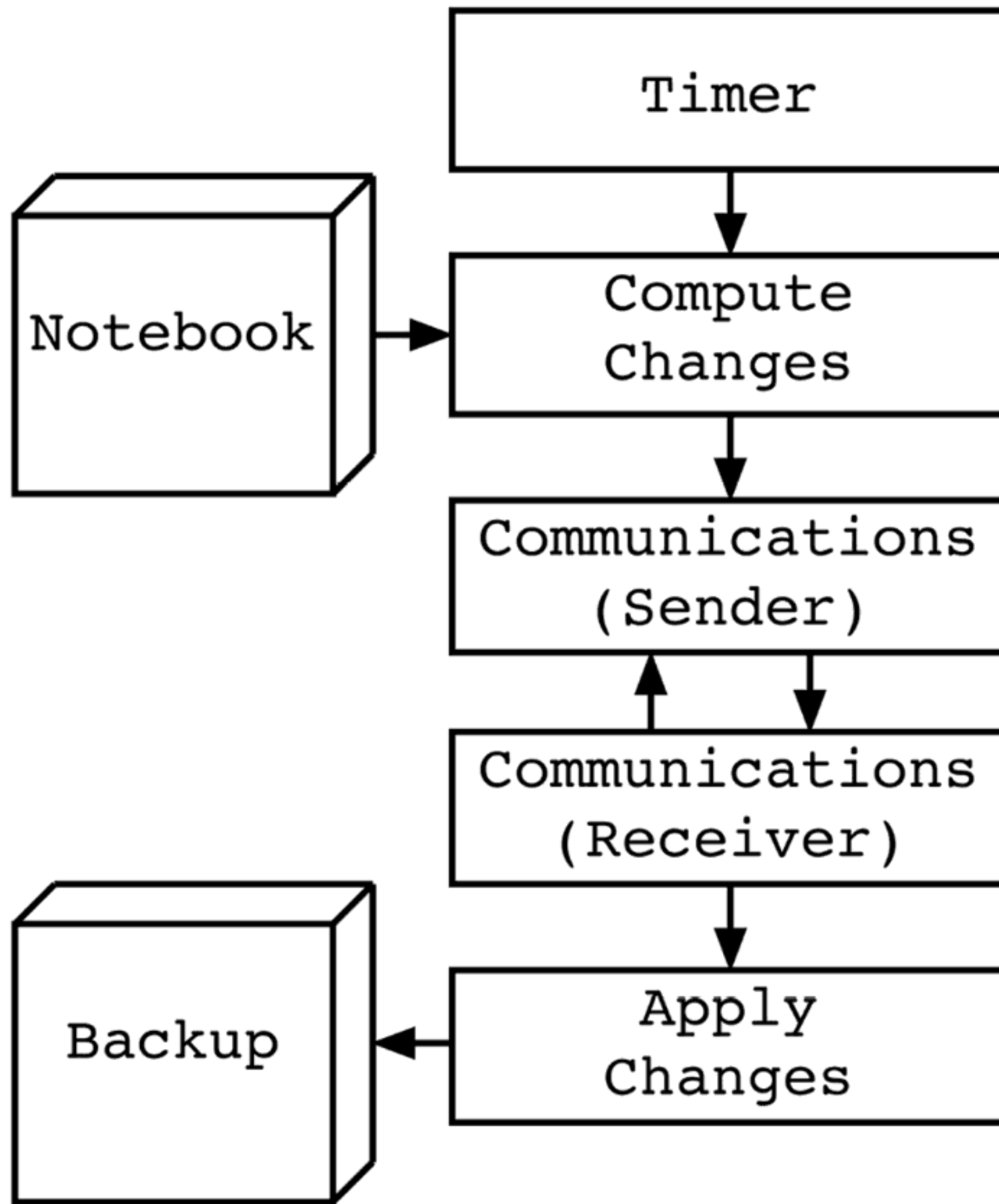
“Levels?” asked the steward.

“Levels of design,” confirmed Marcus while mentally searching for an appropriate example.

“Consider the Spell of Mirroring, which I use to back up my notebooks,” offered Marcus. “Before I wrote the spell, I had to design it carefully. At a high level, I decided to use a simple approach that syncs out data every ten seconds. To reduce the overhead, the spell only communicates the changes since the last update.

“Given this high-level design, I needed four modules: a magical timer, a module to compute changes, a module to handle communication, and a module to merge in the changes at the other end.”

Marcus produced a piece of chalk from his pocket and drew a simple diagram on a nearby wooden table. The steward's mouth scrunched into a hard line, but he didn't interrupt.



“I also specified the interface between the modules. Here I focused on making the interfaces simple, keeping the intermodule connections to a minimum, and hiding internal information. That way, I could focus on writing each module individually and only worry about their interactions through the defined interfaces.

“Then, of course, I wrote the modules themselves. The magical timer was especially finicky, but most satisfying.”

“That seems like a lot of work,” said Shelly. “What if you had gotten to the implementation and found a problem with the structure? Then you would’ve wasted all that time.”

“It’s the opposite,” explained Marcus, while also planning out his later ‘discussion’ on manners with Shelly. “A good design helps you avoid problems, because you are planning the spell in advance.

“Writing a spell without designing it is like trying to plan a five-course meal while you’re already cooking. Before you’re done, you find yourself with an undercooked lamb, too many radishes, and no soup course. Tears might also be involved, depending on the exact circumstances.”

“I have seen it happen,” agreed the steward solemnly.

The group stood in silence, contemplating the image. Shelly shuddered.

“We should be off,” Marcus said, returning to the task at hand. “There’s work to be done.”

The steward nodded. “Thank you for your time. I look forward to your continued progress.”

“I’m always at your service,” responded Marcus.

Two minutes later, Marcus and Shelly walked across the drawbridge, heading back toward the lab.

“Back to the scroll?” asked Shelly.

“Not yet,” answered Marcus. “If I’m going to make any progress, I need more information. I need to go see Agatha.”

Shelly stopped. “Agatha? The woman who talks to worms?” she asked.

“She’s a powerful wizard, if a bit odd,” said Marcus as he continued to walk. “And you will show her the respect that she deserves. While I allow a level of informality in the workshop, you must use her correct title and refer to her as Wizard Agatha.”

Shelly jogged to catch up with him again.

“But she talks to worms,” she said.

“That’s no excuse for informality,” said Marcus.

Shelly felt her face flush. “I understand, sir,” she said.

Marcus continued, “Agatha has learned to embrace her new bond with the worms, and it’s that particular talent I need.”

“You need to talk to worms?” asked Shelly.

“Yes,” said Marcus.

They walked in silence for another quarter mile before Shelly noticed that they were heading in the wrong direction. “If we’re going to see Agatha, then why are we walking toward New Atlantis and the workshop?”

“We’ll have to wait until tomorrow to see her,” Marcus answered. “She keeps a unique schedule these days. I doubt she’d be up now.”

“Isn’t there a saying about an early worm?” asked Shelly.

“You shouldn’t joke about such things,” Marcus responded severely.

Marcus could see the shocked look on her face, but he didn’t bother to explain. There are some things that can’t be understood until you’ve spent time with a wizard that speaks to worms.

After a minute of silence, Marcus spoke, “Anyway, there’s much to do before we go. I need you to go shopping. Pick up three loaves of bread from Breadista’s shop, a dozen eggs from the chicken wrangler, and a fresh cask of orange juice. No pulp! I hate chewing my juice in the morning.”

“Breadista’s?” asked Shelly, panic seeping into her voice.

Marcus looked at her.

“Of course,” said Marcus. “He has the best bread. Is there a problem?”

“It’s just that Breadista’s shop is the opposite direction from the

chicken district. Sir Loaf is much closer.”

Marcus sighed. “Sir Loaf is a low-quality chain baker. His bread is made at a factory in Turington, frozen, and shipped in. And he doesn’t carry raisin loaf.”

Shelly opened her mouth to argue but then hesitated. Marcus made an exasperated gesture. “Fine. I’ll stop at Breadista’s myself. I need to go out and pick up some potion ingredients anyway.”

## The Dangers of Bad Names

Marcus waited in front of the apothecary's counter for a full minute before noisily clearing his throat.

"Excuse me. I'm looking for powdered rose petals," said Marcus.

"On the shelf behind you," replied the young clerk without looking up. He continued to copy text onto a sheet of parchment.

Marcus turned and studied the shelf again. A quick search confirmed the lack of powdered rose petals. Marcus turned back to the clerk.

"I didn't see it there," responded Marcus. "In fact, I didn't see any ingredients I recognize. Everything seems to be encoded."

"Shortened," said the clerk.

Before Marcus could ask for clarification, the clerk hopped off his stool and walked around the counter. He proceeded to the nearest shelf, selected a small bottle, and returned to the counter. He placed the bottle on the counter.

"That will be three copper pieces," said the clerk.

Marcus studied the bottle. In large letters, the label stated: "RP3p". He picked up the bottle and turned it over in his hands, searching for other markings. There were none.

"Are you sure this is powdered rose petals?" Marcus asked.

"Oh yes," the clerk said. "This one clearly states 'RP3p,' which means 'rose petals powdered.'"

"I see. You abbreviated it. RP for rose petals and p for powdered. But why the 3?" asked Marcus.

"There's more than one ingredient that can be abbreviated as RP," answered the clerk. "RP1 is raspberry puree, RP2 is red pollen, RP3 is rose petals, and so forth."

"Rotten prunes?" asked Marcus.

"RP10," answered the clerk.

"Rodent pellets?"

"RP9."

"Raw power?"

"Uh ... I don't think we carry that."

"That system is terribly confusing," said Marcus.

"It's my own scheme. It's more efficient," the clerk explained.

"More efficient? You have to figure out awkward abbreviations in order to understand anything," objected Marcus. "It's a wonder that anyone can find what they need."

"The abbreviations all make sense," responded the clerk. "They're all quite simple. How else would you abbreviate rose petals?"

"I wouldn't!" answered Marcus. "I would label each ingredient with its proper name."

"But that's so tedious," complained the young clerk. "Every day, I copy down the names of hundreds of potions I sell to patrons. I have to

do that all by hand. Do you know how much faster it is to copy potions with this new system? I save hours.”

“My word!” exclaimed Marcus. “You sell potions that use this idiotic encoding? Are you serious?”

The clerk didn’t respond.

“Do you know how dangerous that is?” argued Marcus. “What if one of your customers confuses rose petals and rabbit pellets? It could be a disaster! The smell alone could clear out four city blocks.”

“But it’s more efficient,” protested the clerk.

“For you—and at the moment,” countered Marcus. “But it makes the potion recipes harder to understand. Worse, it makes it easier to make mistakes.”

“The abbreviations are shorter,” tried the clerk.

Marcus shook his head. “I know it seems faster and more efficient now, but there’s a high price for using such shortcuts. It’s better to use clear names. Trust me. I have confused ingredients before; it never ends well.”

“You have?” asked the clerk.

“I once copied down a recipe with S for Salt. Unfortunately, three weeks later, I mistakenly read it as Sulfur. S for sulfur seems quite reasonable, right? Needless to say, the omelets tasted terrible—completely inedible.”

The clerk appeared at a loss. His face contorted as he searched for a new argument to justify the time savings. Finally, he admitted defeat. “I guess I could change them back.”

“You should,” encouraged Marcus. “Now, are you absolutely sure that this is the ingredient I need?”

The clerk hesitated.

“I see,” said Marcus. “I’ll be back some other time, then.”

And with that, Marcus left the store. He turned down a side street and started for the Potion Ingredients Plus shop on the other side of town. It was a long walk and the prices were higher, but he needed to be certain that he had the correct ingredients. The last time he had incorrectly mixed up a batch of magic soap, he had smelled like skunk for a week. There were some things on which he refused to take any chances.



## Version Control

Marcus loved the challenge of developing new spells. He loved breaking problems into components, creating solutions, and combining them into a single coherent spell. It could take him months to perfect a spell to solve a difficult problem. That complexity was why Marcus firmly believed in the importance of version control.

At the end of every day, he would have his apprentice copy his current spell onto a fresh roll of parchment. The apprentice would label the parchment with that day's date and file it in a special drawer. Because of this, if Marcus ever needed access to an old version of his work, he could simply retrieve the correct parchment. Copying scrolls wasn't glamorous work, but Marcus considered it a valuable learning opportunity for the apprentice.

Later that night, as he handed Shelly his latest notes on Hannaldous's spell, she sighed loudly. It was a dramatic, put-upon sigh meant to prompt questions of "What's wrong?" or even "Are you okay?" She felt it delivered the perfect blend of exhaustion (45%), depression (35%), and ennui (20%). She had been practicing.

Marcus ignored her.

Shelly started complaining anyway. "Why do I have to keep copying your spells? You have everything in your notebook already, and you're going to change it again tomorrow. Like this paragraph on mixing the potion—yesterday, I copied almost the exact same thing, except today you crossed out 'Stir 3 times clockwise' and replaced it with 'Stir 4 times counterclockwise.' Why did I bother copying it yesterday? Why can't I wait until you're finished?"

"Two reasons," Marcus began. He enjoyed explaining the logic behind good spell development almost as much as he enjoyed spell development itself. "First, for safety. Do you remember last month when I accidentally set the room on fire? I had been working on the spell to cure dry skin. My lab notebook burned up."

"That was an exceptional case," protested Shelly. "How often do you set your notebook on fire? And if you just made copies of the final product, you would never lose a finished spell."

Even as she spoke, Shelly considered her own question. In the time that she had been Marcus's apprentice, he had managed to set five different notebooks on fire. Maybe he did have a point about backing up his work.

"I would have still lost days of valuable work!" exclaimed Marcus. "A complex spell might take months to develop. It's simply not worth the risk."

"Wait. Aren't you already using a magic mirroring spell on your notebook?" asked Shelly.

Marcus smiled. "Yes. I mirror all my notebooks to a castle out in the

country. But there's another reason to copy my notes: developing a spell isn't always a straight-line process. Sometimes, I make mistakes and need to go back to what I did before."

Shelly looked confused.

"Remember when you copied the spell for silencing marching bands?" Marcus asked.

Shelly nodded. Of all the spells she had seen Marcus develop, that was her favorite. She had experimented with it during her brother's high school bocce game. In the middle of a song, the instruments had gone silent. It had been wondrous. Of course, Shelly still felt guilty that she hadn't bothered to learn the reverse spell.

"While I was developing that spell, I changed a section at the end," continued Marcus. "I removed all of the instructions for using the wand and started over. I threw out two weeks' worth of work."

Shelly remembered clearly. She had muttered a lot of nasty things under her breath when she had seen the paragraphs crossed out.

"Then what happened?" asked Marcus.

Shelly thought back. "You put the instructions back in a few days later."

"Yes!" agreed Marcus. "It turns out that I hadn't factored the wind into the spell. I was able to modify the wording instead. The original wand instructions were fine."

Marcus stared off into space and smiled as though reliving one of the great moments of his life. Shelly's recollection of the events involved less smiling and more muttering.

"I don't understand," said Shelly.

"Version control allows you to go back and recover previous versions," explained Marcus. "If I change my mind and alter an instruction, I cross it out in my notebook. It's gone from my notebook and the mirrored copies. But I might need to go back and look at the old version."

"Why not keep everything in the current notebook?" asked Shelly. "You could add comments saying 'Don't do this' or 'Ignore this' so that you know which instructions are old. That way you never need to throw anything out."

"That would be too messy, like Hannaldous's spell," argued Marcus. "Version control is cleaner. I can make whatever changes I want, and I know that I can always go back to a previous version if I need it."

"But ..." started Shelly, but she had run out of arguments. She could remember many instances when Marcus had made major changes to a spell, only to backtrack the next day. During the development of the Spell of Singing Rocks, he had introduced a critical bug in both the pitch and the volume controls during one revision. As the rocks belted out a shrill rendition of "We Will Rock You," she had sprinted to the file cabinet to retrieve the spell's previous version.

"But ... my hand hurts from copying the same instructions over and over," Shelly finally admitted.

Marcus tried to look sympathetic. “I know it can be a tiresome task. That’s why I have apprentices do it for me.”  
Shelly didn’t feel any better.

## Debugging

At a little after six the next morning, Marcus and Shelly set off to visit Agatha. She lived on an abandoned farm in the outskirts of Grassford. The grounds provided an expansive home to the families of worms she supported. Rumor had it that Agatha spent most of her days running through the fields to scare away birds.

“How does she talk to them? The worms, I mean,” Shelly asked after they had walked a few miles.

“Magic,” replied Marcus.

Shelly rolled her eyes. “I knew that. It has to be magic. I’ve never heard of anyone born with the ability to talk to anything smaller than an fanged mountain turtle, and I think that’s an old myth.

“And why?” Shelly pressed. “Who casts a spell to talk to worms?”

Marcus said nothing.

“Oh!” exclaimed Shelly as a thought struck her. “Is it a curse? Did someone curse her?”

Marcus stopped walking and turned to her. His face was hard.

“Agatha was not cursed,” he said. “And you should be careful how you discuss her ... situation. She can be sensitive about it.”

“Oh. Sorry,” Shelly mumbled.

Marcus nodded and continued walking. After a minute of silence, he spoke again. “It was an accident.”

Shelly glanced over. Marcus stared at the ground as he walked, seemingly mesmerized by the speckling of rocks in the dirt.

When Marcus didn’t continue, she asked, “An accident?”

“Agatha was perhaps the most talented student in my year,” said Marcus. “We were apprentices with Wizard Calciate at the same time. She mastered every spell effortlessly. She even excelled at spell design. She was amazing.

“Then, things fell apart. That spell was supposed to give her the ability to talk to small woodland creatures like chipmunks or squirrels. Unfortunately, she overshot. She gained the ability to speak with worms, lice, and flies. For obvious reasons, she prefers to spend her time talking to worms.”

“Oh,” said Shelly.

Marcus shrugged. “She insists that she’s thrilled with the results,” he said. “But she has been a little ... off since the spell.”

“I see,” said Shelly. “And her talent will help us now?”

“I hope so,” said Marcus.

“How?”

“We need to find out what went wrong with the spell, and it’s too late for debugging, I’m afraid.”

“Debugging?”

“An advanced form of magic,” Marcus said. His face brightened as he

spoke. “Magical debuggers allow you to step through a spell as it executes. This allows you to examine the interior variables of the spell as they change. You can see what’s happening as the spell unfolds.”

“You watch a spell execute with extra information?” asked Shelly. “That must be like flipping through a dictionary. There would be a ton of information flying past in a blur. How could that possibly help?”

Marcus laughed. “I assure you, it’s better than that. Debugging allows you to step through a spell. You can pause after each action and watch how it unfolds.

“Think about the Spell of Bread De-Staling, where you turn a rock-hard loaf of bread into something edible. After the initial chants and the flash of light, what happens?”

Shelly groped around in her head for an answer. Finally, she settled on the obvious. “The bread becomes un-stale?”

“Yes. But what really happens?”

“I’m not sure,” Shelly admitted. “It happens so fast. I figured it was just magic.”

“It is magic, but many steps of magic. First the spell flows into the bread. You can see the location of the spell change. Then the spell shifts moisture around inside the bread. It looks much like a WHILE loop. With a debugger, you can track the internal state of the bread at each step.”

“Really?” asked Shelly.

Marcus stopped walking and rummaged in his pockets. Eventually, he produced an old biscuit. He wasn’t sure why it had been in his pocket or how long it had been there, but it was perfect for his demonstration. He tapped on it to confirm its rock-like staleness.

Then he spoke quietly for a while, making a few precise movements with his hand.

“Watch,” he said.

Marcus started to perform the Spell of Bread De-Staling. Glowing information popped into existence above the biscuit, like a tiny holographic scoreboard.

“Wow,” said Shelly.

She read the information labeled in the tiny infographic:

```
LoopIteration = 0
MoistureContent = 0.1
AirSpeed = 1.33
```

“I’ll step forward one iteration of the loop,” said Marcus. The information changed:

```
LoopIteration = 1
MoistureContent = 0.2
AirSpeed = 1.38
```

“And another iteration,” said Marcus.

```
LoopIteration = 2
MoistureContent = 0.3
AirSpeed = 1.45
```

“What do you see?” he asked.

“The loop iteration is increasing and the moisture content is going up,” said Shelly. She leaned in closer to the floating text.

“What else?” asked Marcus as he advanced the spell another step.

```
LoopIteration = 3
MoistureContent = 0.4
AirSpeed = 1.51
```

“The air speed is increasing,” said Shelly, sounding unsure.

“Exactly,” said Marcus. With a wave of his hand the debugger stopped and the infographic disappeared. “Few wizards ever notice that the air moves faster around the bread, but it’s essential for the spell. The bread constantly needs new air to provide moisture, so the spell has to cycle the air around the target. You can tell a lot about whether the spell is working from the AirSpeed variable alone.”

“Wow,” said Shelly again. Her eyes grew wide as she thought about the implications. “So much information,” she breathed. “It could take forever to step through a long spell, though. Something like the Spell of Extra Butter could take years.”

“You don’t have to step through every action,” Marcus assured her. “You can set breakpoints in your spell. The spell will chug along until it hits a breakpoint. Then it will stop and let you step through. You can set it going again until the next breakpoint whenever you want.”

“That seems useful,” said Shelly.

“Admittedly, using magical debugging isn’t terribly exciting when the spell goes according to plan,” said Marcus. “But it’s invaluable for understanding what’s happening inside a broken spell. As I recall, you could have used more information about the state variables of the kitchen mop during last week’s exercise.”

Shelly recalled the fleeing puddles. She still had no idea what had gone wrong.

“Can you teach me?” asked Shelly.

“When you’re ready.”

“How about the castle? Can I watch the debugging?”

“Unfortunately, it’s too late for debugging,” replied Marcus. “In this case, we must resort to worms.”

“Deworming then?” asked Shelly.

Marcus gave a dry laugh. “It’s too late to observe the spell in action,” he explained. “So we have to poke around at what’s left and try to piece together what happened. The worms will help us inspect the walls’ current state. With any luck, there will be something left—a residual cruft that Hannaldous forgot to clean up.”

“It doesn’t sound as good as debugging,” said Shelly.

“Oh, it isn’t. It’s like trying to understand what happened to a ship based on the shipwreck. You lose vital information about what happened during the accident.”

By this point, they had reached the dirt lane leading to Agatha’s farm. Shelly noticed a worried look cross Marcus’s face as he turned up the lane toward the farmhouse. He hurriedly brushed the traveling dust from his cloak.

They walked onto a small porch, where Marcus wiped his feet twice before proceeding to the door. He knocked. Inside, Shelly could hear the shuffle of someone moving.

Marcus leaned close to Shelly and whispered in her ear, “Whatever you do, don’t make any worm jokes.” His breath smelled unusually minty.

When the door opened, Marcus’s eyes lit up brighter than Shelly had thought possible.

“Agatha!” he exclaimed. “It’s amazing to see you again.”