tundra C-cycling and its role as a source or sink of C and through this its role in the global climate system.[5]

This paragraph reiterates the entire proposal, laying out the problem, challenge, research, and how it will solve the problem. This takes a half-page, which seems like a lot when you're struggling with a page limit. But the feedback from the program officer suggested that this barely squeezed over the line into the "funded" category. We'll never know whether that resolution paragraph was what gave it the million-dollar nudge, but I do know that a reviewer's opinion is sometimes not solidified until the end. So end strong.

EXERCISES

9.1. Analyze published papers

Examine the resolutions of the papers you are evaluating. Do they effectively resolve? Do they briefly sum up the most important results? Do they answer the question? Do they close the circle by returning to the big problem identified in the opening? If not, how would you rewrite the resolution to achieve these goals?

9.2. Write a short article

Do the same exercise for the short articles you and your peers are writing.

5. From M. Weintraub, lead PI, "The Changing Seasonality of Tundra Nutrient Cycling: Implications for Ecosystem and Arctic System Functioning," funded by the U.S. National Science Foundation's Arctic System Science Program.

10

Internal Structure

I figured out, over and over, point A, where the chapter began, and point B, where it ended, and what needed to happen to get my people from A to B.
—Anne Lamott, *Bird by Bird*

OCAR defines the overall structure of a story. The opening grabs your attention with characters and a setting that you care about. The challenge creates uncertainty and curiosity: what is going to happen to those characters? Novelists describe that as creating "tension"—the emotional drive to keep reading. The action feeds you information and develops the story. Finally, the resolution rewards your efforts and relieves the tension—our hero and heroine finally get together, our questions are answered! We may not feel the emotional intensity in a science paper that we do in a good novel, but the tension that keeps us reading is fundamentally the same—it's grounded in curiosity. We don't bother reading a paper if we already know the story. This flow of opening, development, and resolution—building and then rewarding curiosity—creates a story's "arc" (figure 10.1). The vision of story as arc also emerges from the idea that a story has a spiral structure, moving forward but coming back, at the end, to where it began.

Scientific writing is successful when it creates that flow and that arc. But papers and proposals are made up of sections, each of which tells its own story and has

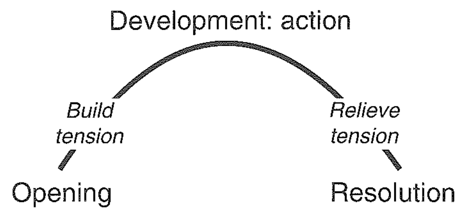

Figure 10.1. A story arc.

its own arc. The Introduction tells us why you did the work—it opens, narrows, and resolves with the paper's overall challenge. The Materials and Methods starts with the study system, then the measurements, and wraps up with how you analyzed the data. The Discussion, too, should form a story of its own, as I argued in chapter 9. It opens by restating the issue, discusses the evidence, and resolves with the paper's conclusion.

These major sections, however, are built of discrete modules: subsections that describe a single method, a single data set, or a single argument. Those subsections should be written to package complete ideas—that is, form story arcs of their own. When you describe a method, you should tell us what information you were trying to gain and what you did to get it. In describing a result, give the overview, the specifics, and the significance.

Going further, each subsection is built of units finer still: individual paragraphs, sentences, and clauses within a sentence. Each tells its own story and has its own structure—they should each form an arc. A story, therefore, doesn't have just a single overall arc, but a hierarchical structure, with small arcs nested within larger ones, ultimately creating the whole (figure 10.2). This hierarchy is analogous to the structure of matter: quarks within protons within atoms within molecules.

A good story works when this hierarchical structure works. Each little arc draws readers forward—it grabs them with a local opening, engages them with a snippet of action, and then rewards them with a resolution. Each forms one turn of the spiral, and step-by-step, carries the reader from the initial issue to the final resolution.

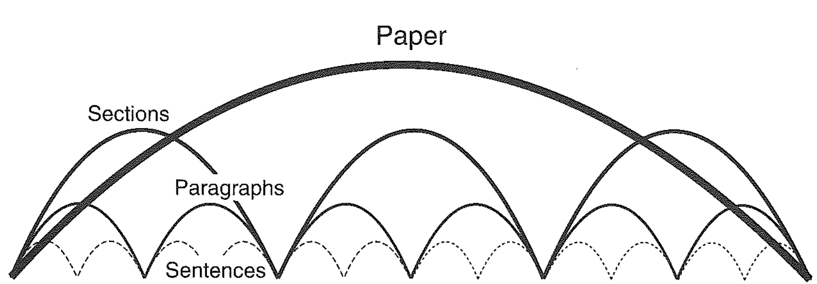

Figure 10.2. A story is a set of nested arcs.

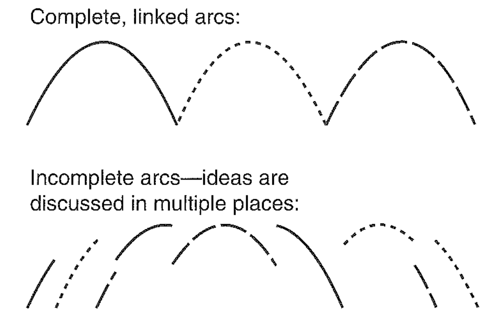

Figure 10.3. Complete versus broken story arcs: beginnings and endings are power positions.

Creating arcs compartmentalizes your thoughts and makes them manageable. It works because we learn by placing information into an established framework. For each new point we build a structure: we give the context and then describe the information, which makes a small story arc. That provides context for the next point, allowing us to construct increasingly complex stories one piece at a time. This is like computer programming. Good programs are built from subroutines or objects, each of which is internally complete; they interact with others by passing specific pieces of *processed* information. Bad programs look like plates of spaghetti. Writing is linear, so we have to lay out these modules in series, each building from the previous.

Effective arcs make it easier for readers to deal with multiple ideas in a single paper. Compare the visual patterns when you link three complete arcs and when you break them up and intersperse them (figure 10.3). The two patterns each contain three arcs and take the same amount of space, but the bottom one is painful to look at (it makes me dizzy). When you write that way, it's just as painful.

Arc structure is effective as well because beginnings and endings are power positions. They emphasize the information contained there, saying *this* is an important point. Without such positions, readers have a hard time distinguishing what is more important from what is less. Creating discrete arcs creates and highlights those power positions. In the top panel of figure 10.3, there are four: the beginning, the end, and the two connecting points in the middle. The bottom panel loses those points; even the beginning and ending are muddled.

10.1. EFFECTIVE ARCS

The last six chapters were all about how to build effective story arcs. They focused on the entire paper, with its opening, action, and resolution. The same principles, however, apply at every level of organization. I've discussed at length how to create the arc of the Introduction (chapters 5–7) and touched on the Discussion (chapter 8). Here I illustrate how to use the same principles to write effective subsections before going on to even finer scales—paragraphs and sentences—in the following chapters.

Let's look at some examples of sections from papers that make effective story arcs. The first is from a paper that evaluated patterns of nitrogen retention in watersheds in the Eastern United States. Nitrogen enters these watersheds from atmospheric deposition, fertilizer, and sewage treatment plants. It runs into rivers as nitrate (NO_3^-) and is ultimately flushed into the ocean. The authors found that in southern watersheds, less of the N entering them reached the ocean; these watersheds "retained" more N. They analyzed the factors that caused this pattern and developed a hypothesis that the warmer ecosystems in the South allowed more biological denitrification, in which NO_3^- is converted to gaseous products: nitrous oxide (N_2O) and N_2. The following section develops one piece of that overall story, evaluating the effect of human population on the proportion of N retained versus exported. I flagged important points with numbers in curly brackets.

Example 10.1

{1} Population density

{2} Increased N export has been shown to be related to increased human population density. {3} If northern watersheds had higher population densities than more southern systems, it is possible that the attendant increase in N input could potentially result in less watershed processing and hence an increase in proportionate riverine export in northern systems. {4} However, the ranges of population densities in northern and southern watersheds overlapped considerably, and, for a given density, the proportion of N export was always higher in northern systems than in southern ones. When all watersheds were considered together, there was a significant relationship between population density and riverine export due only to the influence of the three most densely populated watersheds (the Charles, Blackstone, and Schuylkill). {5} We conclude that population density cannot explain the difference in N export between northern and southern watersheds, but it is a factor to consider for explaining high N export in some watersheds.[1]

{1} The passage starts with a subhead to identify the issue: human population density.

{2} This is the opening (O), which identifies the topic and characters: N export and human population density.

{3} This poses the challenge (C): if northern watersheds have more people they might export more N.

1. S. C. Schaeffer and M. Alber, "Temperature Controls a Latitudinal Gradient in the Proportion of Watershed Nitrogen Exported to Coastal Ecosystems," *Biogeochemistry* 85 (2007):333–46.

{4} Here, the action (A) starts. The authors briefly analyze the data before coming to the climax: the apparent relationship between export and population density was driven by just three rivers.

{5} The story resolves (R) with the statement "We conclude that population density cannot explain the difference in N export between northern and southern watersheds." The phrase "We conclude" is a flag that this is a resolution point.

This passage contains an entire OCAR story arc that completes the discussion of human population density—this is the last time the paper discuses it. After this, the authors move on to analyze other factors that might explain greater N retention in southern watersheds. This is an effective use of story arc structure.

A second example is from a paper that is also about global N cycling, but which asks the question: "What processes cause N to be in short supply in many terrestrial ecosystems?" When the atmosphere is 78 percent nitrogen (N_2) and bacteria can convert that N into biologically available forms, why are plants limited by N? The specific section discusses N relative to carbon (C) and how organisms have characteristic ratios of those elements in their tissues.

Example 10.2

Stoichiometry

Organisms use essential elements at characteristic ratios, and these ratios differ systematically among different groups of organisms. Element ratios are widely used in the analysis of marine ecosystems. Their application is usually less explicit in terrestrial ecology, but they provide the basis for using critical element ratios to predict element mineralization or immobilization during decomposition. One general feature of terrestrial ecosystems is that C:element ratios in plants, especially trees, are much wider than those in other organisms as a consequence of plants' use of C-based compounds (cellulose, lignin) to provide structure. For N in particular, soil bacteria generally have a C:N ratio near 6, while plants often have C:N ratios > 100. Even the leaf litter produced in forests on infertile soils can have C:N ratios in excess of 100.

Consequently, relative to their own requirements, animals and microbes live in a C-rich, N-poor world. Animal nutrition and growth are often constrained by the N content of their food, and protein deficiency is widespread. This difference in stoichiometry can sustain N limitation to animals even where plants are not limited by N supply. Microbes also encounter little N (relative to their requirements) in the plant litter they decompose, and so they retain the N they obtain from their substrate and acquire more directly from inorganic pools in the soil. As a result, N cycling from organic matter back to biologically available forms lags behind the decomposition of plant litter.[2]

2. P. M. Vitousek, S. Hättenschwiler, L. Olander, and S. Allison, "Nitrogen and Nature," *Ambio* 31 (2002): 97–101.

This example opens by defining the overall issue and characters (organisms, essential elements, and characteristic ratios). The two paragraphs discuss these ratios and how they vary among different groups of organisms. It resolves by telling us about why organisms are N-limited: "As a result, N cycling from organic matter back to biologically available forms lags behind the decomposition of plant litter." This section tells a discrete story, one that helps build the larger argument.

What sets this passage off from example 10.1 is that these authors split the story into two paragraphs, each of which makes its own arc. The first paragraph develops the idea that all organisms have characteristic element ratios, but it focuses on plants. That focus is established in the first sentence: "One general feature of terrestrial ecosystems is that C:element ratios in plants, especially trees, are much wider than those in other organisms." Although one sentence starts by mentioning bacteria, it ends by saying "while plants often have C:N ratios > 100," returning the stress to plants. The last sentence of the paragraph starts with "Even the leaf litter," making plants the sentence's subject, and so closes the story arc about plants.

The second paragraph, in contrast, opens with "Consequently, relative to their own requirements, animals and microbes," which makes animals and microbes, the organisms that *consume* plants, the prime characters. All the sentences in this paragraph are about plant consumers, rather than about plants. Thus, it makes a story of its own.

Together, these paragraphs explain why organismal stoichiometry regulates N flow through an ecosystem and why N limits plant growth. The authors could have written this as one long paragraph, but it is stronger this way—each paragraph forms an independent arc. They linked them together with the word *consequently* and in the second paragraph by picking up the idea that the environment is C-rich and N-poor.

Through the devices of subheads, paragraph breaks, and flag words such as *however* and *consequently*, successful authors guide the reader through story arcs and arguments. Individual arcs integrate to form the overall paper. Watching your arcs and ensuring they are coherent and connected gives structure and flow to your writing. Making and resolving complete story arcs makes the reader's job easy.

10.2. ARCLESS WRITING

When writing lacks clear story arcs, it becomes an incoherent mass with no obvious direction, no internal structure, and no points of clear emphasis. The reader may learn little from the work, or worse, they may misinterpret it. Example 10.3 illustrates such arcless, and artless, writing.

> Example 10.3
> California supports rich fisheries off its coast. The high productivity of fish is supported by high rates of algal production. Algal growth in the ocean is typically limited by nitrogen supply, but this is high off California because N-rich deep water wells up to the surface along the coast. This upwelling is driven by winds that push the south-flowing surface water away from the shore, allowing deep water to rise to the surface. These off-shore winds are driven by regional climate patterns, including El Niño, that are being intensified by the greenhouse effect, which results from increased CO_2 in the atmosphere. Increased CO_2 in the atmosphere also increases the amount of CO_2 dissolved in the ocean, which reacts with water to form carbonic acid (H_2CO_3), reducing the ocean's pH. This reduced pH makes it hard for shell-forming organisms to make calcium carbonate shells, and so may reduce the productivity of important marine species such as abalone, oysters, and even sea urchins. Thus, increasing atmospheric CO_2 is going to have many important effects on marine ecosystems.

I find this paragraph completely incoherent, but I wrote it to be that way. Importantly, though, it isn't incoherent because the sentences are unclear; they aren't—each is a simple declarative statement. It also isn't incoherent because the sentences don't link together. Rather, the opposite is true: each sentence builds tightly off the idea developed in the previous one. Look at the ideas each sentence starts and ends with. They tie together seamlessly.

California . . . fisheries
Fish . . . algae
Algae . . . nitrogen . . . upwelling
Upwelling . . . winds
Winds . . . climate
Climate . . . greenhouse effect . . . CO_2
CO_2 . . . acid . . . reduced pH
Reduced pH . . . damage to shell-forming organisms
Thus, . . . CO_2 will affect marine ecosystems.

The problem is that although the sentences flow, they don't flow anywhere in particular. This feels like the result of a game where the first person writes a sentence, passes it to the next person, who writes one and passes it on to the next. The paragraph opens by identifying characters of California and its fisheries, but then keeps adding new characters and new directions—first nitrogen and upwelling, winds and climate, CO_2, acidification, shellfish, and finally marine ecosystems. It then ends with a resolution statement that, although true, has no closure back to the opening.

This paragraph lacked thematic coherence. As a result, the story was unclear. Is it about how climate change will affect California fisheries? Or is the fisheries example intended to illustrate the larger theme of climate effects on oceans?

The paragraph is incoherent because it fails to develop the OCAR functions into an effective structure. There is no clear point and no arc to the story. It drifts. This kind of writing can emerge because the authors never knew where they were going, or because they got distracted in the middle by CO_2 and allowed the story to float off into uncharted and unplanned territory. In revising a paragraph like this one, you need to figure out what the story arcs are and break them into separate units.

Example 10.4
California supports rich fisheries off its coast. The high productivity of fish is supported by high rates of algal production. Algal growth in the ocean is typically limited by nitrogen supply, and is high off the California coast because N-rich deep water wells up to the surface along the coast. This upwelling is driven by winds that push the south-flowing surface water away from the shore, allowing deep water to rise to the surface. These winds are driven by regional climate patterns, including El Niño, that are being intensified by the greenhouse effect. Thus, the productivity of California fisheries will likely change as a result of climate warming, and the changes may result via complex and unexpected mechanisms such as changes in ocean circulation patterns.

In addition, increasing CO_2 is causing the pH of the ocean to decline, and this may have separate but important effects on California fisheries. As CO_2 increases in the atmosphere, more dissolves into the ocean as carbonic acid (H_2CO_3) . . .

Now this passage is structured in coherent arcs—the first, main one, is about how fishery productivity is driven by ocean circulation and thus is sensitive to climate change. Then I pulled the information about acidification into a separate arc that follows but connects to the first one through the climate change-CO_2 link and the language "in addition." By creating linked arcs, the writing gained coherence and SUCCES-type "simplicity." Instead of being a complex mass of interwoven information, it now has a series of simple messages that together add up to a larger, equally simple message: increasing atmospheric CO_2 is going to alter California fisheries.

This kind of arcless writing usually results from what I call "stream of consciousness" writing, in which the author puts down each thought as they come to mind, one idea stimulating another and all flowing onto the page. Many inexperienced authors write this way. Undergraduate essays written the night before the deadline are notorious for this, with no visible structure, ideas appearing in multiple places, and incomplete arguments. Even experienced writers find extraneous thoughts inserting themselves—one sentence sparks a thought, and into the paragraph it goes. What distinguishes an experienced writer is that those extraneous thoughts don't survive to the final draft. If they are interesting and germane, they go into their own arc elsewhere, otherwise they go in the trash.

To ensure that your final pieces have an effective internal structure, go over them paragraph by paragraph and section by section and ask the following questions:

Does each unit make a single, clear point?
When several paragraphs together form a section, are the linkages among them clear?

Has every extraneous thought that breaks the serial arc structure been removed?
When you introduce a topic, do you resolve that discussion before introducing a new topic?
Is every major unit of the work defined by either a subhead or clear opening text?

If you can't answer "Yes" to each of these questions, then you haven't finished working on the structure.

EXERCISES

10.1. Analyze published papers

Go back, once again, to the papers you've been analyzing. This time look at their internal structure. Can you block out sections that form complete arcs? How do the authors indicate that they are beginning or ending arcs? Identify the theme of each arc and give it a subheader that describes that theme.

10.2. Write a short article

Go back again to your short article. Evaluate your own story arcs. Do you form complete arcs, or do you have ideas that keep cropping up in multiple places? Rewrite to ensure clear, well-defined arcs.