The Cathedral and the Bazaar

by Eric S. Raymond $Date: 1998/11/22 04:01:20 $

I anatomize a successful open-source project, fetchmail, that was run as a deliberate test of some surprising theories about software engineering suggested by the history of Linux. I discuss these theories in terms of two fundamentally different development styles, the "cathedral" model of most of the commercial world versus the "bazaar" model of the Linux world. I show that these models derive from opposing assumptions about the nature of the software-debugging task. I then make a sustained argument from the Linux experience for the proposition that "Given enough eyeballs, all bugs are shallow", suggest productive analogies with other self-correcting systems of selfish agents, and conclude with some exploration of the implications of this insight for the future of software.

Contents

1 The Cathedral and the Bazaar

Linux is subversive. Who would have thought even five years ago that a world-class operating system could coalesce as if by magic out of part-time hacking by several thousand developers scattered all over the planet, connected only by the tenuous strands of the Internet?

Certainly not I. By the time Linux swam onto my radar screen in early 1993, I had already been involved in Unix and open-source development for ten years. I was one of the first GNU contributors in the mid-1980s. I had released a good deal of open-source software onto the net, developing or co-developing several programs (nethack, Emacs VC and GUD modes, xlife, and others) that are still in wide use today. I thought I knew how it was done.

Linux overturned much of what I thought I knew. I had been preaching the Unix gospel of small tools, rapid prototyping and evolutionary programming for years. But I also believed there was a certain critical complexity above which a more centralized, a priori approach was required. I believed that the most important software (operating systems and really large tools like Emacs) needed to be built like cathedrals, carefully crafted by individual wizards or small bands of mages working in splendid isolation, with no beta to be released before its time.

Linus Torvalds's style of development - release early and often, delegate everything you can, be open to the point of promiscuity - came as a surprise. No quiet, reverent cathedral-building here – rather, the Linux community seemed to resemble a great babbling bazaar of differing agendas and approaches (aptly symbolized by the Linux archive sites, who'd take submissions from *anyone*) out of which a coherent and stable system could seemingly emerge only by a succession of miracles.

The fact that this bazaar style seemed to work, and work well, came as a distinct shock. As I learned my way around, I worked hard not just at individual projects, but also at trying to understand why the Linux world not only didn't fly apart in confusion but seemed to go from strength to strength at a speed barely imaginable to cathedral-builders.

By mid-1996 I thought I was beginning to understand. Chance handed me a perfect way to test my theory, in the form of an open-source project which I could consciously try to run in the bazaar style. So I did – and it was a significant success.

In the rest of this article, I'll tell the story of that project, and I'll use it to propose some aphorisms about effective open-source development. Not all of these are things I first learned in the Linux world, but we'll see how the Linux world gives them particular point. If I'm correct, they'll help you understand exactly what it is that makes the Linux community such a fountain of good software – and help you become more productive yourself.

2 The Mail Must Get Through

Since 1993 I'd been running the technical side of a small free-access ISP called Chester County InterLink (CCIL) in West Chester, Pennsylvania (I co-founded CCIL and wrote our unique multiuser bulletin-board software – you can check it out by telnetting to *locke.ccil.org* `<telnet://locke.ccil.org>`. Today it supports almost three thousand users on thirty lines.) The job allowed me 24-hour-a-day access to the net through CCIL's 56K line – in fact, it practically demanded it!

Accordingly, I had gotten quite used to instant Internet email. For complicated reasons, it was hard to get SLIP to work between my home machine (snark.thyrsus.com) and CCIL. When I finally succeeded, I found having to periodically telnet over to locke to check my mail annoying. What I wanted was for my mail to be delivered on snark so that I would be notified when it arrived and could handle it using all my local tools.

Simple sendmail forwarding wouldn't work, because my personal machine isn't always on the net and doesn't have a static IP address. What I needed was a program that would reach out over my SLIP connection and pull across my mail to be delivered locally. I knew such things existed, and that most of them used a simple application protocol called POP (Post Office Protocol). And sure enough, there was already a POP3 server included with locke's BSD/OS operating system.

I needed a POP3 client. So I went out on the net and found one. Actually, I found three or four. I used pop-perl for a while, but it was missing what seemed an obvious feature, the ability to hack the addresses on fetched mail so replies would work properly.

The problem was this: suppose someone named 'joe' on locke sent me mail. If I fetched the mail to snark and then tried to reply to it, my mailer would cheerfully try to ship it to a nonexistent 'joe' on snark. Hand-editing reply addresses to tack on '@ccil.org' quickly got to be a serious pain.

This was clearly something the computer ought to be doing for me. But none of the existing POP clients knew how! And this brings us to the first lesson:

1. Every good work of software starts by scratching a developer's personal itch.

Perhaps this should have been obvious (it's long been proverbial that "Necessity is the mother of invention") but too often software developers spend their days grinding away for pay at programs they neither need nor love. But not in the Linux world – which may explain why the average quality of software originated in the Linux community is so high.

So, did I immediately launch into a furious whirl of coding up a brand-new POP3 client to compete with the existing ones? Not on your life! I looked carefully at the POP utilities I had in hand, asking myself "which one is closest to what I want?". Because

2. Good programmers know what to write. Great ones know what to rewrite (and reuse).

While I don't claim to be a great programmer, I try to imitate one. An important trait of the great ones is constructive laziness. They know that you get an A not for effort but for results, and that it's almost always easier to start from a good partial solution than from nothing at all.

Linus Torvalds `<http://www.tuxedo.org/~esr/faqs/linus>`, for example, didn't actually try to write Linux from scratch. Instead, he started by reusing code and ideas from Minix, a tiny Unix-like OS for 386 machines. Eventually all the Minix code went away or was completely rewritten – but while it was there, it provided scaffolding for the infant that would eventually become Linux.

In the same spirit, I went looking for an existing POP utility that was reasonably well coded, to use as a development base.

The source-sharing tradition of the Unix world has always been friendly to code reuse (this is why the GNU project chose Unix as a base OS, in spite of serious reservations about the OS itself). The Linux world has taken this tradition nearly to its technological limit; it has terabytes of open sources generally available. So spending time looking for some else's almost-good-enough is more likely to give you good results in the Linux world than anywhere else.

And it did for me. With those I'd found earlier, my second search made up a total of nine candidates – fetchpop, PopTart, get-mail, gwpop, pimp, pop-perl, popc, popmail and upop. The one I first settled on was 'fetchpop' by Seung-Hong Oh. I put my header-rewrite feature in it, and made various other improvements which the author accepted into his 1.9 release.

A few weeks later, though, I stumbled across the code for 'popclient' by Carl Harris, and found I had a problem. Though fetchpop had some good original ideas in it (such as its daemon mode), it could only handle POP3 and was rather amateurishly coded (Seung-Hong was a bright but inexperienced programmer, and both traits showed). Carl's code was better, quite professional and solid, but his program lacked several important and rather tricky-to-implement fetchpop features (including those I'd coded myself).

Stay or switch? If I switched, I'd be throwing away the coding I'd already done in exchange for a better development base.

A practical motive to switch was the presence of multiple-protocol support. POP3 is the most commonly used of the post-office server protocols, but not the only one. Fetchpop and the other competition didn't do POP2, RPOP, or APOP, and I was already having vague thoughts of perhaps adding *IMAP* `<http://www.imap.org>` (Internet Message Access Protocol, the most recently designed and most powerful post-office protocol) just for fun.

But I had a more theoretical reason to think switching might be as good an idea as well, something I learned long before Linux.

3. "Plan to throw one away; you will, anyhow." (Fred Brooks, "The Mythical Man-Month", Chapter 11)

Or, to put it another way, you often don't really understand the problem until after the first time you implement a solution. The second time, maybe you know enough to do it right. So if you want to get it right, be ready to start over *at least* once.

Well (I told myself) the changes to fetchpop had been my first try. So I switched.

After I sent my first set of popclient patches to Carl Harris on 25 June 1996, I found out that he had basically lost interest in popclient some time before. The code was a bit dusty, with minor bugs hanging out. I had many changes to make, and we quickly agreed that the logical thing for me to do was take over the program.

Without my actually noticing, the project had escalated. No longer was I just contemplating minor patches to an existing POP client. I took on maintaining an entire one, and there were ideas bubbling in my head that I knew would probably lead to major changes.

In a software culture that encourages code-sharing, this is a natural way for a project to evolve. I was acting out this:

4. If you have the right attitude, interesting problems will find you.

But Carl Harris's attitude was even more important. He understood that

5. When you lose interest in a program, your last duty to it is to hand it off to a competent successor.

Without ever having to discuss it, Carl and I knew we had a common goal of having the best solution out there. The only question for either of us was whether I could establish that I was a safe pair of hands. Once I did that, he acted with grace and dispatch. I hope I will act as well when it comes my turn.

3 The Importance of Having Users

And so I inherited popclient. Just as importantly, I inherited popclient's user base. Users are wonderful things to have, and not just because they demonstrate that you're serving a need, that you've done something right. Properly cultivated, they can become co-developers.

Another strength of the Unix tradition, one that Linux pushes to a happy extreme, is that a lot of users are hackers too. Because source code is available, they can be *effective* hackers. This can be tremendously useful for shortening debugging time. Given a bit of encouragement, your users will diagnose problems, suggest fixes, and help improve the code far more quickly than you could unaided.

6. Treating your users as co-developers is your least-hassle route to rapid code improvement and effective debugging.

The power of this effect is easy to underestimate. In fact, pretty well all of us in the open-source world drastically underestimated how well it would scale up with number of users and against system complexity, until Linus Torvalds showed us differently.

In fact, I think Linus's cleverest and most consequential hack was not the construction of the Linux kernel itself, but rather his invention of the Linux development model. When I expressed this opinion in his presence once, he smiled and quietly repeated something he has often said: "I'm basically a very lazy person who likes to get credit for things other people actually do." Lazy like a fox. Or, as Robert Heinlein might have said, too lazy to fail.

In retrospect, one precedent for the methods and success of Linux can be seen in the development of the GNU Emacs Lisp library and Lisp code archives. In contrast to the cathedral-building style of the Emacs C core and most other FSF tools, the evolution of the Lisp code pool was fluid and very user-driven. Ideas and prototype modes were often rewritten three or four times before reaching a stable final form. And loosely-coupled collaborations enabled by the Internet, a la Linux, were frequent.

Indeed, my own most successful single hack previous to fetchmail was probably Emacs VC mode, a Linux-like collaboration by email with three other people, only one of whom (Richard Stallman, the author of Emacs and founder of the *FSF* `<http://www.fsf.org>`) I have met to this day. It was a front-end for SCCS, RCS and later CVS from within Emacs that offered "one-touch" version control operations. It evolved from a tiny, crude sccs.el mode somebody else had written. And the development of VC succeeded because, unlike Emacs itself, Emacs Lisp code could go through release/test/improve generations very quickly.

4 Release Early, Release Often

Early and frequent releases are a critical part of the Linux development model. Most developers (including me) used to believe this was bad policy for larger than trivial projects, because early versions are almost by definition buggy versions and you don't want to wear out the patience of your users.

This belief reinforced the general commitment to a cathedral-building style of development. If the overriding objective was for users to see as few bugs as possible, why then you'd only release one every six months (or less often), and work like a dog on debugging between releases. The Emacs C core was developed this way. The Lisp library, in effect, was not – because there were active Lisp archives outside the FSF's control, where you could go to find new and development code versions independently of Emacs's release cycle.

The most important of these, the Ohio State elisp archive, anticipated the spirit and many of the features of today's big Linux archives. But few of us really thought very hard about what we were doing, or about what the very existence of that archive suggested about problems in FSF's cathedral-building development model. I made one serious attempt around 1992 to get a lot of the Ohio code formally merged into the official Emacs Lisp library. I ran into political trouble and was largely unsuccessful.

But by a year later, as Linux became widely visible, it was clear that something different and much healthier was going on there. Linus's open development policy was the very opposite of cathedral-building. The sunsite and tsx-11 archives were burgeoning, multiple distributions were being floated. And all of this was driven by an unheard-of frequency of core system releases.

Linus was treating his users as co-developers in the most effective possible way:

7. Release early. Release often. And listen to your customers.

Linus's innovation wasn't so much in doing this (something like it had been Unix-world tradition for a long time), but in scaling it up to a level of intensity that matched the complexity of what he was developing. In those early times (around 1991) it wasn't unknown for him to release a new kernel more than once a *day!* Because he cultivated his base of co-developers and leveraged the Internet for collaboration harder than anyone else, this worked.

But *how* did it work? And was it something I could duplicate, or did it rely on some unique genius of Linus Torvalds?

I didn't think so. Granted, Linus is a damn fine hacker (how many of us could engineer an entire production-quality operating system kernel?). But Linux didn't represent any awesome conceptual leap forward. Linus is not (or at least, not yet) an innovative genius of design in the way that, say, Richard Stallman or James Gosling (of NeWS and Java) are. Rather, Linus seems to me to be a genius of engineering, with a sixth sense for avoiding bugs and development dead-ends and a true knack for finding the minimum-effort path from point A to point B. Indeed, the whole design of Linux breathes this quality and mirrors Linus's essentially conservative and simplifying design approach.

So, if rapid releases and leveraging the Internet medium to the hilt were not accidents but integral parts of Linus's engineering-genius insight into the minimum-effort path, what was he maximizing? What was he cranking out of the machinery?

Put that way, the question answers itself. Linus was keeping his hacker/users constantly stimulated and rewarded – stimulated by the prospect of having an ego-satisfying piece of the action, rewarded by the sight of constant (even *daily*) improvement in their work.

Linus was directly aiming to maximize the number of person-hours thrown at debugging and development, even at the possible cost of instability in the code and user-base burnout if any serious bug proved intractable. Linus was behaving as though he believed something like this:

8. Given a large enough beta-tester and co-developer base, almost every problem will be characterized quickly and the fix obvious to someone.

Or, less formally, "Given enough eyeballs, all bugs are shallow." I dub this: "Linus's Law".

My original formulation was that every problem "will be transparent to somebody". Linus demurred that the person who understands and fixes the problem is not necessarily or even usually the person who first characterizes it. "Somebody finds the problem," he says, "and somebody *else* understands it. And I'll go on record as saying that finding it is the bigger challenge." But the point is that both things tend to happen quickly.

Here, I think, is the core difference underlying the cathedral-builder and bazaar styles. In the cathedral-builder view of programming, bugs and development problems are tricky, insidious, deep phenomena. It takes months of scrutiny by a dedicated few to develop confidence that you've winkled them all out. Thus the long release intervals, and the inevitable disappointment when long-awaited releases are not perfect.

In the bazaar view, on the other hand, you assume that bugs are generally shallow phenomena – or, at least, that they turn shallow pretty quick when exposed to a thousand eager co-developers pounding on every single new release. Accordingly you release often in order to get more corrections, and as a beneficial side effect you have less to lose if an occasional botch gets out the door.

And that's it. That's enough. If "Linus's Law" is false, then any system as complex as the Linux kernel, being hacked over by as many hands as the Linux kernel, should at some point have collapsed under the weight of unforseen bad interactions and undiscovered "deep" bugs. If it's true, on the other hand, it is sufficient to explain Linux's relative lack of bugginess.

And maybe it shouldn't have been such a surprise, at that. Sociologists years ago discovered that the averaged opinion of a mass of equally expert (or equally ignorant) observers is quite a bit more reliable a predictor than that of a single randomly-chosen one of the observers. They called this the "Delphi effect". It appears that what Linus has shown is that this applies even to debugging an operating system – that the Delphi effect can tame development complexity even at the complexity level of an OS kernel.

I am indebted to Jeff Dutky <dutky@wam.umd.edu> for pointing out that Linus's Law can be rephrased as "Debugging is parallelizable". Jeff observes that although debugging requires debuggers to communicate with some coordinating developer, it doesn't require significant coordination between debuggers. Thus it doesn't fall prey to the same quadratic complexity and management costs that make adding developers problematic.

In practice, the theoretical loss of efficiency due to duplication of work by debuggers almost never seems to be an issue in the Linux world. One effect of a "release early and often policy" is to minimize such duplication by propagating fed-back fixes quickly.

Brooks even made an off-hand observation related to Jeff's: "The total cost of maintaining a widely used program is typically 40 percent or more of the cost of developing it. Surprisingly this cost is strongly affected by the number of users. *More users find more bugs*." (my emphasis).

More users find more bugs because adding more users adds more different ways of stressing the program. This effect is amplified when the users are co-developers. Each one approaches the task of bug characterization with a slightly different perceptual set and analytical toolkit, a different angle on the problem. The "Delphi effect" seems to work precisely because of this variation. In the specific context of debugging, the variation also tends to reduce duplication of effort.

So adding more beta-testers may not reduce the complexity of the current "deepest" bug from the *developer's* point of view, but it increases the probability that someone's toolkit will be matched to the problem in such a way that the bug is shallow *to that person*.

Linus coppers his bets, too. In case there *are* serious bugs, Linux kernel version are numbered in such a way that potential users can make a choice either to run the last version designated "stable" or to ride the cutting edge and risk bugs in order to get new features. This tactic is not yet formally imitated by most Linux hackers, but perhaps it should be; the fact that either choice is available makes both more attractive.

5 When Is A Rose Not A Rose?

Having studied Linus's behavior and formed a theory about why it was successful, I made a conscious decision to test this theory on my new (admittedly much less complex and ambitious) project.

But the first thing I did was reorganize and simplify popclient a lot. Carl Harris's implementation was very sound, but exhibited a kind of unnecessary complexity common to many C programmers. He treated the code as central and the data structures as support for the code. As a result, the code was beautiful but the data structure design ad-hoc and rather ugly (at least by the high standards of this old LISP hacker).

I had another purpose for rewriting besides improving the code and the data structure design, however.

That was to evolve it into something I understood completely. It's no fun to be responsible for fixing bugs in a program you don't understand.

For the first month or so, then, I was simply following out the implications of Carl's basic design. The first serious change I made was to add IMAP support. I did this by reorganizing the protocol machines into a generic driver and three method tables (for POP2, POP3, and IMAP). This and the previous changes illustrate a general principle that's good for programmers to keep in mind, especially in languages like C that don't naturally do dynamic typing:

9. Smart data structures and dumb code works a lot better than the other way around.

Brooks, Chapter 9: "Show me your [code] and conceal your [data structures], and I shall continue to be mystified. Show me your [data structures], and I won't usually need your [code]; it'll be obvious."

Actually, he said "flowcharts" and "tables". But allowing for thirty years of terminological/cultural shift, it's almost the same point.

At this point (early September 1996, about six weeks from zero) I started thinking that a name change might be in order – after all, it wasn't just a POP client any more. But I hesitated, because there was as yet nothing genuinely new in the design. My version of popclient had yet to develop an identity of its own.

That changed, radically, when fetchmail learned how to forward fetched mail to the SMTP port. I'll get to that in a moment. But first: I said above that I'd decided to use this project to test my theory about what Linus Torvalds had done right. How (you may well ask) did I do that? In these ways:

1. I released early and often (almost never less often than every ten days; during periods of intense development, once a day).
2. I grew my beta list by adding to it everyone who contacted me about fetchmail.
3. I sent chatty announcements to the beta list whenever I released, encouraging people to participate.
4. And I listened to my beta testers, polling them about design decisions and stroking them whenever they sent in patches and feedback.

The payoff from these simple measures was immediate. From the beginning of the project, I got bug reports of a quality most developers would kill for, often with good fixes attached. I got thoughtful criticism, I got fan mail, I got intelligent feature suggestions. Which leads to:

10. If you treat your beta-testers as if they're your most valuable resource, they will respond by becoming your most valuable resource.

One interesting measure of fetchmail's success is the sheer size of the project beta list, fetchmail-friends. At time of writing it has 249 members and is adding two or three a week.

Actually, as I revise in late May 1997 the list is beginning to lose members from its high of close to 300 for an interesting reason. Several people have asked me to unsubscribe them because fetchmail is working so well for them that they no longer need to see the list traffic! Perhaps this is part of the normal life-cycle of a mature bazaar-style project.

6 Popclient becomes Fetchmail

The real turning point in the project was when Harry Hochheiser sent me his scratch code for forwarding mail to the client machine's SMTP port. I realized almost immediately that a reliable implementation of this feature would make all the other delivery modes next to obsolete.

For many weeks I had been tweaking fetchmail rather incrementally while feeling like the interface design was serviceable but grubby – inelegant and with too many exiguous options hanging out all over. The options to dump fetched mail to a mailbox file or standard output particularly bothered me, but I couldn't figure out why.

What I saw when I thought about SMTP forwarding was that popclient had been trying to do too many things. It had been designed to be both a mail transport agent (MTA) and a local delivery agent (MDA). With SMTP forwarding, it could get out of the MDA business and be a pure MTA, handing off mail to other programs for local delivery just as sendmail does.

Why mess with all the complexity of configuring a mail delivery agent or setting up lock-and-append on a mailbox when port 25 is almost guaranteed to be there on any platform with TCP/IP support in the first place? Especially when this means retrieved mail is guaranteed to look like normal sender-initiated SMTP mail, which is really what we want anyway.

There are several lessons here. First, this SMTP-forwarding idea was the biggest single payoff I got from consciously trying to emulate Linus's methods. A user gave me this terrific idea – all I had to do was understand the implications.

11. The next best thing to having good ideas is recognizing good ideas from your users. Sometimes the latter is better.

Interestingly enough, you will quickly find that if you are completely and self-deprecatingly truthful about how much you owe other people, the world at large will treat you like you did every bit of the invention yourself and are just being becomingly modest about your innate genius. We can all see how well this worked for Linus!

(When I gave this paper at the Perl conference in August 1997, Larry Wall was in the front row. As I got to the last line above he called out, religious-revival style, "Tell it, tell it, brother!". The whole audience laughed, because they knew it had worked for the inventor of Perl too.)

After a very few weeks of running the project in the same spirit, I began to get similar praise not just from my users but from other people to whom the word leaked out. I stashed away some of that email; I'll look at it again sometime if I ever start wondering whether my life has been worthwhile :-).

But there are two more fundamental, non-political lessons here that are general to all kinds of design.

12. Often, the most striking and innovative solutions come from realizing that your concept of the problem was wrong.

I had been trying to solve the wrong problem by continuing to develop popclient as a combined MTA/MDA with all kinds of funky local delivery modes. Fetchmail's design needed to be rethought from the ground up as a pure MTA, a part of the normal SMTP-speaking Internet mail path.

When you hit a wall in development – when you find yourself hard put to think past the next patch – it's often time to ask not whether you've got the right answer, but whether you're asking the right question. Perhaps the problem needs to be reframed.

Well, I had reframed my problem. Clearly, the right thing to do was (1) hack SMTP forwarding support into the generic driver, (2) make it the default mode, and (3) eventually throw out all the other delivery modes, especially the deliver-to-file and deliver-to-standard-output options.

I hesitated over step 3 for some time, fearing to upset long-time popclient users dependent on the alternate delivery mechanisms. In theory, they could immediately switch to .forward files or their non-sendmail equivalents to get the same effects. In practice the transition might have been messy.

But when I did it, the benefits proved huge. The cruftiest parts of the driver code vanished. Configuration got radically simpler – no more grovelling around for the system MDA and user's mailbox, no more worries about whether the underlying OS supports file locking.

Also, the only way to lose mail vanished. If you specified delivery to a file and the disk got full, your mail got lost. This can't happen with SMTP forwarding because your SMTP listener won't return OK unless the message can be delivered or at least spooled for later delivery.

Also, performance improved (though not so you'd notice it in a single run). Another not insignificant benefit of this change was that the manual page got a lot simpler.

Later, I had to bring delivery via a user-specified local MDA back in order to allow handling of some obscure situations involving dynamic SLIP. But I found a much simpler way to do it.

The moral? Don't hesitate to throw away superannuated features when you can do it without loss of effectiveness. Antoine de Saint-Exupéry (who was an aviator and aircraft designer when he wasn't being the author of classic children's books) said:

13. "Perfection (in design) is achieved not when there is nothing more to add, but rather when there is nothing more to take away."

When your code is getting both better and simpler, that is when you *know* it's right. And in the process, the fetchmail design acquired an identity of its own, different from the ancestral popclient.

It was time for the name change. The new design looked much more like a dual of sendmail than the old popclient had; both are MTAs, but where sendmail pushes then delivers, the new popclient pulls then delivers. So, two months off the blocks, I renamed it fetchmail.

7 Fetchmail Grows Up

There I was with a neat and innovative design, code that I knew worked well because I used it every day, and a burgeoning beta list. It gradually dawned on me that I was no longer engaged in a trivial personal hack that might happen to be useful to few other people. I had my hands on a program every hacker with a Unix box and a SLIP/PPP mail connection really needs.

With the SMTP forwarding feature, it pulled far enough in front of the competition to potentially become a "category killer", one of those classic programs that fills its niche so competently that the alternatives are not just discarded but almost forgotten.

I think you can't really aim or plan for a result like this. You have to get pulled into it by design ideas so powerful that afterward the results just seem inevitable, natural, even foreordained. The only way to try for ideas like that is by having lots of ideas – or by having the engineering judgment to take other peoples' good ideas beyond where the originators thought they could go.

Andrew Tanenbaum had the original idea to build a simple native Unix for the 386, for use as a teaching tool. Linus Torvalds pushed the Minix concept further than Andrew probably thought it could go – and it grew into something wonderful. In the same way (though on a smaller scale), I took some ideas by Carl Harris and Harry Hochheiser and pushed them hard. Neither of us was 'original' in the romantic way people think is genius. But then, most science and engineering and software development isn't done by original genius, hacker mythology to the contrary.

The results were pretty heady stuff all the same – in fact, just the kind of success every hacker lives for! And they meant I would have to set my standards even higher. To make fetchmail as good as I now saw it could be, I'd have to write not just for my own needs, but also include and support features necessary to others but outside my orbit. And do that while keeping the program simple and robust.

The first and overwhelmingly most important feature I wrote after realizing this was multidrop support – the ability to fetch mail from mailboxes that had accumulated all mail for a group of users, and then route each piece of mail to its individual recipients.

I decided to add the multidrop support partly because some users were clamoring for it, but mostly because I thought it would shake bugs out of the single-drop code by forcing me to deal with addressing in full generality. And so it proved. Getting *RFC 822* `<http://info.internet.isi.edu:80/in-notes/rfc/files/rfc822.txt>` parsing right took me a remarkably long time, not because any individual piece of it is hard but because it involved a pile of interdependent and fussy details.

But multidrop addressing turned out to be an excellent design decision as well. Here's how I knew:

14. Any tool should be useful in the expected way, but a truly great tool lends itself to uses you never expected.

The unexpected use for multi-drop fetchmail is to run mailing lists with the list kept, and alias expansion done, on the *client* side of the SLIP/PPP connection. This means someone running a personal machine through an ISP account can manage a mailing list without continuing access to the ISP's alias files.

Another important change demanded by my beta testers was support for 8-bit MIME operation. This was pretty easy to do, because I had been careful to keep the code 8-bit clean. Not because I anticipated the demand for this feature, but rather in obedience to another rule:

*15. When writing gateway software of any kind, take pains to disturb the data stream as little as possible – and *never* throw away information unless the recipient forces you to!*

Had I not obeyed this rule, 8-bit MIME support would have been difficult and buggy. As it was, all I had to do is read *RFC 1652* `<http://info.internet.isi.edu:80/in-notes/rfc/files/rfc1652.txt>` and add a trivial bit of header-generation logic.

Some European users bugged me into adding an option to limit the number of messages retrieved per session (so they can control costs from their expensive phone networks). I resisted this for a long time, and I'm still not entirely happy about it. But if you're writing for the world, you have to listen to your customers – this doesn't change just because they're not paying you in money.

8 A Few More Lessons From Fetchmail

Before we go back to general software-engineering issues, there are a couple more specific lessons from the fetchmail experience to ponder.

The rc file syntax includes optional 'noise' keywords that are entirely ignored by the parser. The English-like syntax they allow is considerably more readable than the traditional terse keyword-value pairs you get when you strip them all out.

These started out as a late-night experiment when I noticed how much the rc file declarations were beginning to resemble an imperative minilanguage. (This is also why I changed the original popclient 'server' keyword to 'poll').

It seemed to me that trying to make that imperative minilanguage more like English might make it easier to use. Now, although I'm a convinced partisan of the "make it a language" school of design as exemplified by Emacs and HTML and many database engines, I am not normally a big fan of "English-like" syntaxes.

Traditionally programmers have tended to favor control syntaxes that are very precise and compact and have no redundancy at all. This is a cultural legacy from when computing resources were expensive, so parsing stages had to be as cheap and simple as possible. English, with about 50% redundancy, looked like a very inappropriate model then.

This is not my reason for normally avoiding English-like syntaxes; I mention it here only to demolish it. With cheap cycles and core, terseness should not be an end in itself. Nowadays it's more important for a language to be convenient for humans than to be cheap for the computer.

There are, however, good reasons to be wary. One is the complexity cost of the parsing stage – you don't want to raise that to the point where it's a significant source of bugs and user confusion in itself. Another is that trying to make a language syntax English-like often demands that the "English" it speaks be bent seriously out of shape, so much so that the superficial resemblance to natural language is as confusing as a traditional syntax would have been. (You see this in a lot of so-called "fourth generation" and commercial database-query languages.)

The fetchmail control syntax seems to avoid these problems because the language domain is extremely restricted. It's nowhere near a general-purpose language; the things it says simply are not very complicated, so there's little potential for confusion in moving mentally between a tiny subset of English and the actual control language. I think there may be a wider lesson here:

16. When your language is nowhere near Turing-complete, syntactic sugar can be your friend.

Another lesson is about security by obscurity. Some fetchmail users asked me to change the software to store passwords encrypted in the rc file, so snoopers wouldn't be able to casually see them.

I didn't do it, because this doesn't actually add protection. Anyone who's acquired permissions to read your rc file will be able to run fetchmail as you anyway – and if it's your password they're after, they'd be able to rip the necessary decoder out of the fetchmail code itself to get it.

All .fetchmailrc password encryption would have done is give a false sense of security to people who don't think very hard. The general rule here is:

17. A security system is only as secure as its secret. Beware of pseudo-secrets.

9 Necessary Preconditions for the Bazaar Style

Early reviewers and test audiences for this paper consistently raised questions about the preconditions for successful bazaar-style development, including both the qualifications of the project leader and the state of code at the time one goes public and starts to try to build a co-developer community.

It's fairly clear that one cannot code from the ground up in bazaar style. One can test, debug and improve in bazaar style, but it would be very hard to *originate* a project in bazaar mode. Linus didn't try it. I didn't either. Your nascent developer community needs to have something runnable and testable to play with.

When you start community-building, what you need to be able to present is a *plausible promise*. Your program doesn't have to work particularly well. It can be crude, buggy, incomplete, and poorly documented. What it must not fail to do is convince potential co-developers that it can be evolved into something really neat in the foreseeable future.

Linux and fetchmail both went public with strong, attractive basic designs. Many people thinking about the bazaar model as I have presented it have correctly considered this critical, then jumped from it to the conclusion that a high degree of design intuition and cleverness in the project leader is indispensable.

But Linus got his design from Unix. I got mine initially from the ancestral popclient (though it would later change a great deal, much more proportionately speaking than has Linux). So does the leader/coordinator for a bazaar-style effort really have to have exceptional design talent, or can he get by on leveraging the design talent of others?

I think it is not critical that the coordinator be able to originate designs of exceptional brilliance, but it is absolutely critical that the coordinator be able to *recognize good design ideas from others*.

Both the Linux and fetchmail projects show evidence of this. Linus, while not (as previously discussed) a spectacularly original designer, has displayed a powerful knack for recognizing good design and integrating it into the Linux kernel. And I have already described how the single most powerful design idea in fetchmail (SMTP forwarding) came from somebody else.

Early audiences of this paper complimented me by suggesting that I am prone to undervalue design originality in bazaar projects because I have a lot of it myself, and therefore take it for granted. There may be some truth to this; design (as opposed to coding or debugging) is certainly my strongest skill.

But the problem with being clever and original in software design is that it gets to be a habit – you start reflexively making things cute and complicated when you should be keeping them robust and simple. I have had projects crash on me because I made this mistake, but I managed not to with fetchmail.

So I believe the fetchmail project succeeded partly because I restrained my tendency to be clever; this argues (at least) against design originality being essential for successful bazaar projects. And consider Linux. Suppose Linus Torvalds had been trying to pull off fundamental innovations in operating system design during the development; does it seem at all likely that the resulting kernel would be as stable and successful as what we have?

A certain base level of design and coding skill is required, of course, but I expect almost anybody seriously thinking of launching a bazaar effort will already be above that minimum. The open-source community's internal market in reputation exerts subtle pressure on people not to launch development efforts they're not competent to follow through on. So far this seems to have worked pretty well.

There is another kind of skill not normally associated with software development which I think is as important as design cleverness to bazaar projects – and it may be more important. A bazaar project coordinator or leader must have good people and communications skills.

This should be obvious. In order to build a development community, you need to attract people, interest them in what you're doing, and keep them happy about the amount of work they're doing. Technical sizzle will go a long way towards accomplishing this, but it's far from the whole story. The personality you project matters, too.

It is not a coincidence that Linus is a nice guy who makes people like him and want to help him. It's not a coincidence that I'm an energetic extrovert who enjoys working a crowd and has some of the delivery and instincts of a stand-up comic. To make the bazaar model work, it helps enormously if you have at least a little skill at charming people.

10 The Social Context of Open-Source Software

It is truly written: the best hacks start out as personal solutions to the author's everyday problems, and spread because the problem turns out to be typical for a large class of users. This takes us back to the matter of rule 1, restated in a perhaps more useful way:

18. To solve an interesting problem, start by finding a problem that is interesting to you.

So it was with Carl Harris and the ancestral popclient, and so with me and fetchmail. But this has been understood for a long time. The interesting point, the point that the histories of Linux and fetchmail seem to demand we focus on, is the next stage – the evolution of software in the presence of a large and active community of users and co-developers.

In "The Mythical Man-Month", Fred Brooks observed that programmer time is not fungible; adding developers to a late software project makes it later. He argued that the complexity and communication costs of a project rise with the square of the number of developers, while work done only rises linearly. This claim has since become known as "Brooks's Law" and is widely regarded as a truism. But if Brooks's Law were the whole picture, Linux would be impossible.

Gerald Weinberg's classic "The Psychology Of Computer Programming" supplied what, in hindsight, we can see as a vital correction to Brooks. In his discussion of "egoless programming", Weinberg observed that in shops where developers are not territorial about their code, and encourage other people to look for bugs and potential improvements in it, improvement happens dramatically faster than elsewhere.

Weinberg's choice of terminology has perhaps prevented his analysis from gaining the acceptance it deserved – one has to smile at the thought of describing Internet hackers as "egoless". But I think his argument looks more compelling today than ever.

The history of Unix should have prepared us for what we're learning from Linux (and what I've verified experimentally on a smaller scale by deliberately copying Linus's methods). That is, that while coding remains an essentially solitary activity, the really great hacks come from harnessing the attention and brainpower of entire communities. The developer who uses only his or her own brain in a closed project is going to fall behind the developer who knows how to create an open, evolutionary context in which bug-spotting and improvements get done by hundreds of people.

But the traditional Unix world was prevented from pushing this approach to the ultimate by several factors. One was the legal contraints of various licenses, trade secrets, and commercial interests. Another (in hindsight) was that the Internet wasn't yet good enough.

Before cheap Internet, there were some geographically compact communities where the culture encouraged Weinberg's "egoless" programming, and a developer could easily attract a lot of skilled kibitzers and co-developers. Bell Labs, the MIT AI Lab, UC Berkeley – these became the home of innovations that are legendary and still potent.

Linux was the first project to make a conscious and successful effort to use the entire *world* as its talent pool. I don't think it's a coincidence that the gestation period of Linux coincided with the birth of the World Wide Web, and that Linux left its infancy during the same period in 1993-1994 that saw the takeoff of the ISP industry and the explosion of mainstream interest in the Internet. Linus was the first person who learned how to play by the new rules that pervasive Internet made possible.

While cheap Internet was a necessary condition for the Linux model to evolve, I think it was not by itself a sufficient condition. Another vital factor was the development of a leadership style and set of cooperative customs that could allow developers to attract co-developers and get maximum leverage out of the medium.

But what is this leadership style and what are these customs? They cannot be based on power relationships – and even if they could be, leadership by coercion would not produce the results we see. Weinberg quotes the autobiography of the 19th-century Russian anarchist Pyotr Alexeyvich Kropotkin's "Memoirs of a Revolutionist" to good effect on this subject:

"Having been brought up in a serf-owner's family, I entered active life, like all young men of my time, with a great deal of confidence in the necessity of commanding, ordering, scolding, punishing and the like. But when, at an early stage, I had to manage serious enterprises and to deal with [free] men, and when each mistake would lead at once to heavy consequences, I began to appreciate the difference between acting on the principle of command and discipline and acting on the principle of common understanding. The former works admirably in a military parade, but it is worth nothing where real life is concerned, and the aim can be achieved only through the severe effort of many converging wills."

The "severe effort of many converging wills" is precisely what a project like Linux requires – and the "principle of command" is effectively impossible to apply among volunteers in the anarchist's paradise we call the Internet. To operate and compete effectively, hackers who want to lead collaborative projects have to learn how to recruit and energize effective communities of interest in the mode vaguely suggested by Kropotkin's "principle of understanding". They must learn to use Linus's Law.

Earlier I referred to the "Delphi effect" as a possible explanation for Linus's Law. But more powerful analogies to adaptive systems in biology and economics also irresistably suggest themselves. The Linux world behaves in many respects like a free market or an ecology, a collection of selfish agents attempting to maximize utility which in the process produces a self-correcting spontaneous order more elaborate and efficient than any amount of central planning could have achieved. Here, then, is the place to seek the "principle of understanding".

The "utility function" Linux hackers are maximizing is not classically economic, but is the intangible of their own ego satisfaction and reputation among other hackers. (One may call their motivation "altruistic", but this ignores the fact that altruism is itself a form of ego satisfaction for the altruist). Voluntary cultures that work this way are not actually uncommon; one other in which I have long participated is science fiction fandom, which unlike hackerdom explicitly recognizes "egoboo" (the enhancement of one's reputation among other fans) as the basic drive behind volunteer activity.

Linus, by successfully positioning himself as the gatekeeper of a project in which the development is mostly done by others, and nurturing interest in the project until it became self-sustaining, has shown an acute grasp of Kropotkin's "principle of shared understanding". This quasi-economic view of the Linux world enables us to see how that understanding is applied.

We may view Linus's method as a way to create an efficient market in "egoboo" – to connect the selfishness of individual hackers as firmly as possible to difficult ends that can only be achieved by sustained cooperation. With the fetchmail project I have shown (albeit on a smaller scale) that his methods can be duplicated with good results. Perhaps I have even done it a bit more consciously and systematically than he.

Many people (especially those who politically distrust free markets) would expect a culture of self-directed egoists to be fragmented, territorial, wasteful, secretive, and hostile. But this expectation is clearly falsified by (to give just one example) the stunning variety, quality and depth of Linux documentation. It is a hallowed given that programmers *hate* documenting; how is it, then, that Linux hackers generate so much of it? Evidently Linux's free market in egoboo works better to produce virtuous, other-directed behavior than the massively-funded documentation shops of commercial software producers.

Both the fetchmail and Linux kernel projects show that by properly rewarding the egos of many other hackers, a strong developer/coordinator can use the Internet to capture the benefits of having lots of co-developers without having a project collapse into a chaotic mess. So to Brooks's Law I counter-propose the following:

19: Provided the development coordinator has a medium at least as good as the Internet, and knows how to lead without coercion, many heads are inevitably better than one.

I think the future of open-source software will increasingly belong to people who know how to play Linus's game, people who leave behind the cathedral and embrace the bazaar. This is not to say that individual vision and brilliance will no longer matter; rather, I think that the cutting edge of open-source software will belong to people who start from individual vision and brilliance, then amplify it through the effective construction of voluntary communities of interest.

And perhaps not only the future of *open-source* software. No closed-source developer can match the pool of talent the Linux community can bring to bear on a problem. Very few could afford even to hire the more than two hundred people who have contributed to fetchmail!

Perhaps in the end the open-source culture will triumph not because cooperation is morally right or software "hoarding" is morally wrong (assuming you believe the latter, which neither Linus nor I do), but simply because the closed-source world cannot win an evolutionary arms race with open-source communities that can put orders of magnitude more skilled time into a problem.

11 Acknowledgements

This paper was improved by conversations with a large number of people who helped debug it. Particular thanks to Jeff Dutky <dutky@wam.umd.edu>, who suggested the "debugging is parallelizable" formulation, and helped develop the analysis that proceeds from it. Also to Nancy Lebovitz <nancyl@universe.digex.net> for her suggestion that I emulate Weinberg by quoting Kropotkin. Perceptive criticisms also came from Joan Eslinger <wombat@kilimanjaro.engr.sgi.com> and Marty Franz <marty@net-link.net> of the General Technics list. I'm grateful to the members of PLUG, the Philadelphia Linux User's group, for providing the first test audience for the first public version of this paper. Finally, Linus Torvalds's comments were helpful and his early endorsement very encouraging.

12 For Further Reading

I quoted several bits from Frederick P. Brooks's classic *The Mythical Man-Month* because, in many respects, his insights have yet to be improved upon. I heartily recommend the 25th Anniversary edition from Addison-Wesley (ISBN 0-201-83595-9), which adds his 1986 *"No Silver Bullet"* paper.

The new edition is wrapped up by an invaluable 20-years-later retrospective in which Brooks forthrightly admits to the few judgements in the original text which have not stood the test of time. I first read the retrospective after this paper was substantially complete, and was surprised to discover that Brooks attributes bazaar-like practices to Microsoft! (In fact, however, this attribution turned out to be mistaken. In 1998 we learned from the *Halloween Documents* `<http://www.opensource.org/halloween.html>` that Microsoft's internal developer community is heavily balkanized, with the kind of general source access needed to support a bazaar not even truly possible.)

Gerald M. Weinberg's *The Psychology Of Computer Programming* (New York, Van Nostrand Reinhold 1971) introduced the rather unfortunately-labeled concept of "egoless programming". While he was nowhere near the first person to realize the futility of the "principle of command", he was probably the first to recognize and argue the point in particular connection with software development.

Richard P. Gabriel, contemplating the Unix culture of the pre-Linux era, reluctantly argued for the superiority of a primitive bazaar-like model in his 1989 paper *Lisp: Good News, Bad News, and How To Win Big*. Though dated in some respects, this essay is still rightly celebrated among Lisp fans (including me). A correspondent reminded me that the section titled "Worse Is Better" reads almost as an anticipation of Linux. The paper is accessible on the World Wide Web at `<http://www.naggum.no/worse-is-better.html>`.

De Marco and Lister's *Peopleware: Productive Projects and Teams* (New York; Dorset House, 1987; ISBN 0-932633-05-6) is an underappreciated gem which I was delighted to see Fred Brooks cite in his retrospective. While little of what the authors have to say is directly applicable to the Linux or open-source communities, the authors' insight into the conditions necessary for creative work is acute and worthwhile for anyone attempting to import some of the bazaar model's virtues into a commercial context.

Finally, I must admit that I very nearly called this paper "The Cathedral and the Agora", the latter term being the Greek for an open market or public meeting place. The seminal "agoric systems" papers by Mark Miller and Eric Drexler, by describing the emergent properties of market-like computational ecologies, helped prepare me to think clearly about analogous phenomena in the open-source culture when Linux rubbed my nose in them five years later. These papers are available on the Web at `<http://www.agorics.com/agorpapers.html>`.

13 Epilog: Netscape Embraces the Bazaar!

It's a strange feeling to realize you're helping make history....

On January 22 1998, approximately seven months after I first published this paper, Netscape Communications, Inc. announced plans to *give away the source for Netscape Communicator* `<http://www.netscape.com/newsref/pr/newsrelease558.html>`. I had had no clue this was going to happen before the day of the announcement.

Eric Hahn, Executive Vice President and Chief Technology Officer at Netscape, emailed me shortly afterwards as follows: "On behalf of everyone at Netscape, I want to thank you for helping us get to this point in the first place. Your thinking and writings were fundamental inspirations to our decision."

The following week I flew out to Silicon Valley at Netscape's invitation for a day-long strategy conference (on Feb 4 1998) with some of their top executives and technical people. We designed Netscape's source-release strategy and license together, and laid some more plans that we hope will eventually have far-reaching and positive impacts on the open-source community. As I write, it is a bit too soon to be more specific; but details should be forthcoming within weeks.

Netscape is about to provide us with a large-scale, real-world test of the bazaar model in the commercial world. The open-source culture now faces a danger; if Netscape's execution doesn't work, the open-source concept may be so discredited that the commercial world won't touch it again for another decade.

On the other hand, this is also a spectacular opportunity. Initial reaction to the move on Wall Street and elsewhere has been cautiously positive. We're being given a chance to prove ourselves, too. If Netscape regains substantial market share through this move, it just may set off a long-overdue revolution in the software industry.

The next year should be a very instructive and interesting time.

14 Version and Change History

$Id: cathedral-bazaar.sgml,v 1.42 1998/11/22 04:01:20 esr Exp $

I gave 1.16 at the Linux Kongress, May 21 1997.

I added the bibliography July 7 1997 in 1.20.

I added the Perl Conference anecdote November 18 1997 in 1.27.

I changed "free software" to "open source" February 9 1998 in 1.29.

I added "Epilog: Netscape Embraces the Bazaar!" on February 10 1998 in 1.31

I removed Paul Eggert's 'graph on GPL vs. bazaar in response to cogent aguments from RMS on 28 July 1998.

I added a correction of Brooks based on the Halloween Documents on November 20 1998 in 1.40.

Other revision levels incorporate minor editorial and markup fixes.