Quake's Game Engine: The Big Picture | Dr Dobb's

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If you want to be a game programmer, or for that matter, any sort of programmer at all, here's the secret to success in just two words: Ship it. Finish the product and get it out the door, and you'll be a hero. It sounds simple, but it's a surprisingly rare skill, and one that's highly prized by software companies. Here's why.

My friend David Stafford, cofounder of the game company Cinematronics, says that shipping software is an unnatural act, and he's right. Most of the fun stuff in a software project happens early on, when anything's possible and there's a ton of new code to write. By the end of a project, the design is carved in stone, and most of the work involves fixing bugs, or trying to figure out how to shoehorn in yet another feature that wasn't planned in the original design. All that is a lot less fun than starting a project, and often very hard work—but it has to be done before the project can ship. As a former manager of mine liked to say, "After you finish the first 90 percent of a project, you have to finish the other 90 percent." It's that second 90 percent that's the key to success.

This is true for even the most interesting projects. I spent the last year and a half as one of three programmers writing the game *Quake* at id Software. It was a tremendously exciting project: *Quake* was probably the most anticipated game of all time, and our mission was to push multiplayer and 3-D game technology ahead of anything else on the market. Exciting as it was, we hit the same rough patches toward the end as any other software project. I am quite serious when I say that a month before shipping, we were sick to death of working on *Quake*.

A lot of programmers get to that second 90 percent, get tired and bored and frustrated, then change jobs, or lose focus, or find excuses to procrastinate. There are a million ways not to finish a project, but there's only one way to finish: Put your head down and grind it out until it's done. Do that, and I promise, the programming world will be yours.

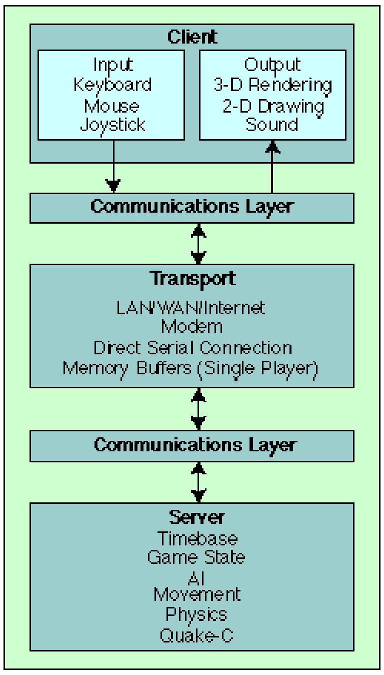
It worked for Dave. Cinematronics became a successful company and was acquired by Maxis. It worked for us at id as well. *DOOM* was one of the most successful games ever, and we wanted to top it. For the programmers, the goal was to set new standards for 3-D and multiplayer—especially Internet—technology for the *DOOM* genre, and *Quake* did just that. Let's take a look at how it works.

Client-Server

DOOM has a synchronous peer-to-peer networking architecture, where each player's machine runs a parallel game engine, and machines proceed in lockstep. This works reasonably well for two-player modem games, but makes it hard to support lots of players coming and going at will, and is less suited to the Internet. So, we went with a different approach for *Quake*.

Quake is a client-server application, as shown in Figure 1. All gameplay and simulation are performed on the server, and all input and output take place on the client, which is basically nothing more than a specialized terminal. Each client gathers up keyboard, mouse, and joystick input for each frame and sends it off to the server; the server receives the input from all clients, runs the game for a fixed timeslice, and sends the results off to the clients; the clients display the results during the next frame.

Figure 1: *Quake's architecture*.



This is true even in single-player mode, but here the client and the server can't actually be separate processes because *Quake* has to run on non-multitasking DOS. Instead, during each frame, the input portion of the client is run, then the server executes, and finally, the output portion of the client displays the current frame, with all communications between the client and the server flowing through the communications layer using memory buffers as the transport. In multiplayer games, the client and server are separate processes, running on different machines (except for the special case of listen servers, where both the multiplayer server and one of the clients run in the same process on one machine).

Client-server technology has obvious benefits for multiplayer games, because it vastly simplifies issues of synchronization between various players. Perhaps less obvious is that client-server is useful even in single-player mode, because it enforces a modular design, and has a single communications channel between client and server that simplifies debugging. It's also a big help to have identical code for single-player and multiplayer modes.

Communications

An interesting issue with client-server architecture is Internet play. *Quake* was designed from the start for multiplayer gaming. Internet play, which hadn't been a major issue for earlier games, raised some interesting and unique issues. Communications latencies are longer over the Internet than they are on a LAN, and often even longer than directly connected modems. Packet delivery also is less reliable.

In the early stages of development, *Quake* used reliable packet delivery for everything. With this approach, packets are sent out and acknowledgment is sent back. If acknowledgment isn't received, everything is brought to a halt until a resend succeeds. This was necessary because, in order to reduce the total amount of data that needed to be sent, the clients were sent only changes to the current state, rather than the current state itself. When sending nothing but changes, it's essential that every change be received, or else the cumulative state will be incorrect.

The problem with reliable packet delivery is this: If a packet gets dropped, it takes a long time to find that out (at least one roundtrip from server to client), and then it takes a long time to resend it (at least another roundtrip). If the ping time to the client is 200ms (about the best possible with a PPP connection), then a dropped packet will result in a glitch of several hundred milliseconds—long enough to be very noticeable and annoying.

Instead, *Quake* now uses reliable packet delivery only for information like scores and level changes. Current game state, like the locations of players and objects, is sent each timeslice in its entirety (not as changes), and is compressed so it doesn't take up too much bandwidth. However, this information is not sent with reliable delivery; there is no acknowledgment, and neither the server nor client knows (or cares) whether those packets arrive. Each update contains all states relevant to each client for that frame, so all a dropped packet means is a freezing of the world for one server timeslice. Server timeslices come in a constant stream at a rate of 10 or 20 a second, so a dropped packet results in a glitch of no more than 100ms, which is quite acceptable.

Latency

Client-server imposes a potentially large latency between a player's action, such as pressing the jump key, and the player seeing the resulting action, such as his viewpoint jumping into the air. The action has to make a roundtrip to the server and back, so the latency can vary from close to no time at all on a LAN, to hundreds of milliseconds on the Internet. Longer latencies can make the game difficult to play; by the time the player actually jumps, he might have moved many feet forward and fallen into a pit. This problem raises the possibility of running some or all of the game logic on the client in parallel with the server, or in parallel with other clients in a peer-to-peer architecture so the client can have faster response.

Faster response is nice, but there are some serious problems with simulating on the client. For one thing, it makes communications and game logic much more difficult, because instead of one central master simulation on the server, there are now potentially a dozen or more simulations that need to be synchronized. Only one outcome from any event can be allowed. So, with client simulation, there must be a mechanism for determining whose decision wins in case of conflict, and undoing actions that are overruled by another simulation. Worse, there are inevitably paradoxes. For example, a player may fire a rocket and see it hit an opponent, but then see the opponent magically resurrected as the local client gets overruled. While *Quake* has lag, it doesn't have paradox, and that helps a lot in making the experience feel real.

Quake does use one shortcut to help with lag: If a player turns to look in another direction, it happens immediately, without waiting for the server to process the input and return the new state. There are no paradoxes or synchronization issues associated with turning in *Quake*, and instant turning makes the game feel much more responsive. (In *QuakeWorld*, a multiplayer-only follow-up currently in development, we've gone a step further and simulated the movement of the player, but nothing else, on the client. We've found that this does improve the feel of Internet play quite a bit, albeit at the cost of an occasional minor paradox.)

The Server

The *Quake* server maintains the game's timebase and state, performs object movement and physics, and runs monster AI. The most interesting aspect of the server is the extent to which it is data-driven. Each level (the current "world") is completely described by object locations and types, wall locations, and so on, stored in a database loaded from disk. The behavior of objects and monsters is likewise externally programmable, controlled by functions written in a built-in interpreted language, Quake-C. Not only have people been able to make new levels, but they've also been able to add new game elements, such as smart rockets that track people, planes that can be climbed into and flown, and alerters that stick to players and screech, "Here I am!"—all without writing a single line of C or assembly code. This flexibility not only makes *Quake* a great platform for creativity, but also helped a great deal as we developed the game because it allowed us to try out changes without having to recompile the program. Indeed, levels and Quake-C programs can be reloaded and tested without even exiting *Quake*.

If you're curious, there's lots of Quake-C code available on the Internet. One excellent site is Quake Developer's Pages (http://www.gamers.org/dEngine/quake/). You can find information about making custom monsters and levels there, as well.

The Client

The server and communications layer are crucial elements of *Quake*, but it's the client with which the player actually interacts, and it's the client that has the glamour component—the 3-D engine. The client also handles keyboard, mouse, and joystick input, sound mixing, and 2-D drawing (such as menus), the status bar, and text messages—but those are straightforward. 3-D is where the action is. The challenges with *Quake*'s 3-D engine were twofold: Allow true 3-D viewing in all directions (unlike *DOOM*'s 2.5-D), and improve visual quality with lighting, more precise pixel placement, or whatever else it took—all with good performance, of course.

As with the server, the 3-D engine is data driven. Drawing data falls into two categories: the world and entities. Each level contains information about the geometry of walls, floors, and so on, and also about the textures (bitmaps) painted onto those faces. The *Quake* database also contains triangle meshes and textures describing entities (players, monsters, and other moving objects). Originally, we planned to draw everything in *Quake* through a single rendering pipeline, but it turned out that there was no way to get good performance out of a single pipeline for both huge walls and monsters made of hundreds of tiny polygons. So, the world and entities are drawn by completely different code paths.

The world is stored as a data structure known as a "Binary Space Partitioning" (BSP) tree. BSP trees are quite complicated to explain, so I won't go into detail here. (If you're interested, I've written about BSP trees in *Dr. Dobb's Sourcebook*; see the 1995 May/June, July/August, and November/ December issues.) For *Quake*'s purposes, BSP trees do two very useful things: They make it easy to traverse a set of polygons in front-to-back or back-to-front order, and they partition space into convex volumes.

Back-to-front order is handy if you're drawing complete polygons, because you can draw all your polygons back-to-front and get correct occlusion, a process known as the "painters algorithm." In *Quake*, however, we draw polygons front-to-back. To be precise, we take all our polygons and put their edges into a global list; then we rasterize this list and draw only the visible (front most) portions. The big advantage of this approach is that we draw each pixel in the world once and only once, saving precious drawing time in complex scenes because we don't overdraw polygons one atop another. (See the May/June and July/August 1996 issues of *Dr. Dobb's Sourcebook* for further discussion of *Quake*'s edge list.)

However, the edge list isn't fast enough to handle the thousands of polygons that can be in the view pyramid. If you put that many edges into an edge list, what you get is a very slow frame rate, because there's just too much data to process and sort. So, we limited the number of polygons that have to be considered by using the convex-partitioning property of BSP trees to calculate a "potentially visible set" (PVS).

When a level is processed into the *Quake* format (a separate preprocessing step done by a utility program once when a map is built), a BSP tree is built from the level, and then, for each convex subspace (called a "leaf") of the BSP tree, a visibility calculation is performed. For a given leaf, the utility calculates which other subspaces are visible from anywhere in that leaf, and that information is stored with the leaf in the BSP tree. In other words, if no matter where you're standing in a kitchen downstairs you can't possibly see up the stairs into the bedroom, then the bedroom polygons are omitted from the kitchen leaf's PVS. If you can see into the living room from the corner of the kitchen, the kitchen leaf's PVS remembers that living room polygons are potentially visible. We can be sure that the PVS for a leaf lists all the polygons we ever need to consider for a player standing anywhere in that leaf.

At rendering time, rather than processing the thousands of polygons in a level, we only have to deal with—clip, transform, project, and insert in the edge list—the few hundred polygons in the current leaf's PVS. This reduces the polygon load to a level that the edge list can handle. The PVS and the edge list together make for fast, consistent performance in a wide variety of scenes. The January/February 1996, *Dr. Dobb's Sourcebook* covers the PVS in more detail.

One point about the PVS: It can be quite expensive to calculate. PVS determination can take 15 or 20 minutes to finish—on a four-processor Alpha system! Fortunately, Pentium Pro systems are getting fast enough to handle the job well, and no doubt the code can be made faster, but be aware that the power of the PVS comes at a price.

Once the edge list has finished processing all the edges, we're left with a set of spans that cover the screen exactly once. We pass this list to a rasterizer that texture maps the appropriate bitmap onto those spans, accounting for perspective (which requires an expensive divide to get exactly right) by doing a divide every 16 pixels, and interpolating linearly between those points. (This is the key step in allowing true 3-D viewing in any direction.)

Lighting, unlike *DOOM*'s crude sector lighting, involves true light sources and shadowing. This is performed by having a separate lighting map (basically a texture map, but with light values instead of colors) for each polygon, with light samples on a 16-pixel grid, and prelighting the texture for each polygon according to the grid as the texture is drawn into a memory buffer. The actual texture mapping works from these prelit textures, with no lighting occurring during the texture mapping itself. I don't have space to explain how this differs from normal lighting, or why it's so desirable, except to say that it results in detailed, high-quality lighting and good performance. You can find a thorough explanation in the November/December 1996 *Dr. Dobb's Sourcebook*.

Entities

DOOM used flat posters—sprites—for monsters and other moving objects, and one of the big advances in *Quake* was switching to polygonal entities that are true 3-D objects. However, this raised a new concern. Entities can contain hundreds of polygons, and there can be a dozen entities visible at once, so drawing them fast was one of our major challenges. Each entity consists of a set of vertices, and a mesh of triangles across those vertices. All the vertices in an entity are transformed and projected as a set, and then all the triangles are drawn, using affine (linear) rather than perspective-correct texture mapping. Affine is faster, and entity polygons are typically so small and far away that the imperfections of affine aren't noticeable. Also, the entity drawer is optimized for small triangles, rather than the long span drawing that the world drawer is optimized for. There's a special ultra-fast drawer for distant entities that you can read about in the January/February 1997 *Dr. Dobb's Sourcebook*.

The big difference, however, is that entities are drawn with z-buffering; that is, the distance of each pixel to be drawn is compared to the distance of the pixel being drawn over (stored in a memory area called a "z-buffer"), and the new pixel is drawn only if it's closer. This lets entities sort seamlessly with the world and each other, no matter where they move or what angle they're viewed at. There's a cost, to be sure; z-buffering is slower than non-z-buffered drawing, and the z-buffer has to be initialized to match the visible world pixels, at a cost of about 10 percent of *Quake*'s performance. That cost is, however, more than repaid by the simplicity and accuracy of z-buffering. It saved us from having to perform complex clipping and sorting operations in order to draw entities properly, and gave us flawless drawing under all circumstances.

The PVS helps improve entity performance, because we only need to draw entities that are in the PVS for the current leaf. Other entities don't exist (as far as the client is concerned), so the server doesn't even bother sending information about anything outside the PVS. This not only helps reduce the drawing load, but also minimizes the amount of information that has to be sent over modems or the Internet.

As a final effect, we wanted to have effects like smoke trails and huge explosions in *Quake*, but couldn't figure out how to do them fast and well with standard sprites (although the cores of explosions are sprites) or with polygon models. The solution was to use clouds of hundreds of square, colored, z-buffered rectangles that scale with distance. These are called "particles." A few hundred particles strewn behind a rocket looks amazingly like a trail of flame and smoke, especially if they start out yellow and fade to red and then to gray. As a group, they do an excellent job of convincing the eye that they represent a true 3-D object.

Particles and unreliable packet delivery, along with dynamic lighting (which allows explosions and muzzle flashes to light up the world) were among the last additions to the *Quake* engine. These features made a well-rendered, but somewhat sterile, world come alive. These, together with details such as menus, a ton of optimization, and a healthy dose of bug fixing, were the "second 90 percent" that propelled *Quake* from being a functional 3-D and multiplayer engine to a technological leap ahead.

Ah, if only we'd had time for a third 90 percent!