they're easy to assemble. You know what it's like on Christmas Eve. You have to get everybody to bed, then you have a lot of pressure because Santa Claus will be coming in the morning so you only have a limited amount of time to assemble these toys. Fisher-Price does the best job of any toy company on making toys that are easy to fabricate and assemble.

"So when we started this airplane program, Dale [Hougardy] and I decided that one thing we could really do that would add value to our airline customers is to make the airplane easier to fabricate and assemble. Because if it's easier to fabricate and assemble, it means it takes less flow time, and it takes less work and you also have less rework because it's easier for people to do it correctly. And I kept thinking for a long time, 'How do we capture the imagination of a design and an operators community?"—having an assignment to design it so that it is easier to make it, fabricate it, and assemble it. For example, if you have a right-hand thread, make it so it only goes on the right hand or on the right-hand part. If it's on the other side, you should do something different with the design of the part so it can only be assembled from that side. Fisher-Price makes a little notch in their wheels so that you can only put the right wheel on the right hub and you can only put the left wheel on the left hub. You also use simple tools. So I started saying what we're after on this program is not just meeting cost targets, not just adding value to our airline customers, but we're going to do what Fisher-Price does on Christmas Eve. We're going to make this easier to fabricate and assemble. So one time, as a present, the engineering guys gave me a whole bunch of Fisher-Price toys so I could pass them out and make the points to the other engineers. Isn't that funny?"

The Boeing plant at Everett is littered with planes in every stage of manufacture. In early 1992 they were 747s and 767s. Wherever you looked, there would be disembodied cockpits or unconnected cylinders of fuselage, waiting to be joined together to become real functioning airplanes. But in one corner of one building there was a plane that would never fly, that could never fly. It was a reminder of how Boeing traditionally designed planes before the 777 came along. From the outside, it looked like a Boeing 747-400 freighter. And inside, too, in the stripped-down lower lobe, it had a full complement of wires, hydraulic tubing, and control cables that you would expect to find in a 747. But this was a design mock-up, a plane built solely to check that the engineers who had produced the drawings that would be used to manufacture the parts of the plane had got it right, and had not made any silly mistakes so that one piece and another did not fit for the same space.

Traditionally, new planes had been designed in two dimensions. Draw-
ings on paper had been used as a basis for the manufacturing process. But to design a plane entirely in this way, with over 100,000 different three-dimensional parts, and then to trust that the two-dimensional drawings had accounted for all the complexities of the three-dimensional airplane would have led to endless unpleasant discoveries at the assembly stage, as a piece designed by one designer arrived at the factory and turned out to be impossible to install because another designer had failed to leave the right amount of space. Furthermore, when it came down to the detail of the plane, the wiring and tubing that ran from one end to the other and required holes to be drilled or cut to allow free passage, the task of accounting for all of those in two-dimensional drawings would have been impossible. So the drawings were backed up by what were called mock-ups—successively refined full-scale models of the plane.

Stage 1 mock-ups were usually made of plywood and foam and enabled all the large pieces to be visualized in three dimensions. The pieces would be cut on the basis of preliminary drawings, and then refinements would be carved in the foam or wood, and the changes fed back into the drawings.

Stage 2 mock-ups added some metal parts and began to address complicated issues of routing wires and tubes as well as the accessibility of pieces that would have to be removed or inspected as part of regular maintenance. This mock-up would also be pored over by manufacturing engineers, as they began to think about designing the machine tools that would make each of the larger components. Finally, a stage 3 mock-up would be constructed, incorporating discoveries and changes made during the first two stages, with every component constructed by hand according to the engineering drawings. With this mock-up, although the materials were not always the same as in the real plane, and the accuracy was not to the fine tolerances of the finished engineering, it was an extremely good way to anticipate and avoid what are called errors, changes, and reworks. But not good enough. With the inevitable imperfections and the overwhelming complexity of such a handcrafted object, there were still unpleasant surprises on the shop floor as the first planes were assembled. The key word was "interferences." When two pieces overlapped in space, they were said to interfere. This could happen with large pieces such as ribs or spars, or tiny components such as a washer that is the wrong size, or a hole that is too small.

Henry Shomber is an engineer who has been with Boeing for nearly forty years. He was brought in very early on the 777 program to help develop new ways of designing planes to avoid some of the problems of the old ways and to cut down the cost of mistakes: "We needed to improve our ability to produc a product that is produced at lower cost and with less change, fewer errors, and fewer requirements to make last-minute changes in order to produce it. We are the world leader, but often I think of it as largely because of our customer support organization. If you own a Boeing airplane—it doesn't matter whether you are the first-tier owner or the third-tier owner—and that airplane is on the ground, we'll help you find a part or build a part for you and get it back in the air. And that's really what makes us the world's best today. What we want to add to that is to make an airplane that is more service ready. If you look back at the 747-400, 757, 767—they weren't as service ready as we would like them to be, and that experience leads us to say we must do something different."

Shomber described graphically the Rube Goldberg way in which all plans up to the 777 had their wiring bundles designed: "We would literally thread the wire bundle through the mock-up and then take it out and flatten it on the board. We'd measure it, and that's the way we decided how long the wire needed to be. And then you would adjust as necessary because the airplane, which is not made of plywood and aluminum, differs from the mock-up. So as you produce those first wire bundles, then you make further adjustments to make them fit the real airplane. Hydraulics too were in a very similar situation."

Dick Johnson, Boeing's chief project engineer for digital product design, highlighted some of the problems that could occur: "You have five thousand engineers designing the airplane. It's very difficult for those engineers to coordinate with two-dimensional pieces of paper, or for a designer who is designing an air-conditioning duct to walk over to somebody who is in Structures and say, 'Now, here's my duct—how does it match up with your structure?' Very difficult with two-dimensional pictures. So we ended up using the mock-up and, quite honestly, also using the final assembly line to finish up the integration. And it's very costly. You end up with an airplane that's very difficult to build. The first time that parts come together is on that assembly line. And they don't fit. So we have a tremendous cost on the first few airplanes of reworking to make sure all the parts fit together."

Solving such problems in the last quarter of the twentieth century was clearly a task for computers. In fact, computer-aided design had been used for some time in the car industry and in architecture, essentially as a drawing tool. But Boeing was after something more ambitious than a draftsman's visual aid, and that required number-crunching ability of a high order, as Alan Mulally explained:

"With digital computers before, we didn't have enough computational capacity to simulate an airplane. We've been able to use computers for parts
of the task, and the best example is the flight-crew-training simulators, where we simulated lots of the airplane’s flying characteristics as well as the systems to teach pilots how to fly. It’s much more effective than flying the real airplane, because you can do so many more different conditions and simulate so much more effectively the different systems and failures of the systems. But as digital computers became larger and could handle more capacity, the next step was how we could make use of them as a design tool. And so in the past, where we had to make mock-up parts and try to figure out how to fit them together, now we can actually simulate the parts and assemblies and we can see ourselves whether all the parts are there and if they fit before we release them to all of the makers around the world. So the essence of what really happened is that this tool allowed Engineering to take responsibility for all their parts before they asked people to make them.

“Now think about this. Before, you’d use a two-dimensional piece of paper and a yellow pencil and we would try to create a three-dimensional product. It was very difficult. It’s very difficult for the mind, and it’s a real skill just to think in two dimensions about all these parts that are really three. So for the first time the engineering creative process was enabled to think in terms of the way the world is, in terms of three dimensions, and look at it and understand it and balance all the objectives of functionality and reliability. Now, computers don’t design airplanes. We have not put the knowledge that’s in the airplane designer’s head into artificial intelligence that balances all these objectives. Some day we’ll probably move to that end, but right now the knowledge to design airplanes is in the designer’s head.”

Nowadays the number of designers and drawings and the interconnectedness of the components of a plane as large as the 777 require such complex systems of numbering, duplicating, and releasing drawings that the computer is about the only way to deal satisfactorily with the process. Gone are the days when more homely methods were sufficient. One retired Boeing engineer, who worked during the Second World War on the design of 3-29 bombers reported that he had seen engineers make sketches on the cuffs of their shirtsleeves and then give the shirt to someone else to copy. As planes got bigger and systems became more complicated, another Boeing engineer put a drawing number on his wrist and "released" himself into circulation to see what happened to his own design drawings when they were sent off to the manufacturing engineers.

To see Boeing’s computer design system in action is as pleasurable as watching a good animated cartoon. On June 16, 1992, John Mahoney, a designer with the Passenger Doors Team, was designing a complex metal solid that would eventually hold the large handle that opened the door. The fineness of detail, the smoothness of rotation, and the delicacy of coloring that appeared on the computer screen would have taken many hours to achieve if he had been working with a paper blueprint. But the workstation took all this in its stride, responding to the designer’s instructions with the speed of light. Mahoney had called up the final three-dimensional contours for this piece and was working out whether he could cut any more metal away and if so, where. At this stage in the project, with 25 percent or so of the drawings finalized, the various designers were paying a lot of attention to the weight requirements of the plane. Any unnecessary ounce or gram translates into extra metal to be carried on a long journey, and extra fuel to carry that metal, and then in an apparently infinite regress there’s the extra fuel needed to carry the weight of the extra fuel needed to carry the extra weight of the part.

Mahoney rotated the component on his screen and drew a circle on one surface. He then told the computer to make a cylinder using that circle as one face. Then he made the cylinder become a hole in the component. A press of a couple of buttons produced an on-screen display of how much weight such a hole would lose, about a fifth of an ounce, compared with leaving it as solid metal. But clearly, cutting holes in pieces to save weight can have a deleterious effect on other aspects of the component, particularly its load-bearing ability. Here another aspect of the system comes into its own as Mahoney gives instructions for the computer to display and then print out a view of the component under stress in a chosen direction, with colored areas marking the different levels of force experienced throughout the metal. Like a colorful weather map, the piece shows one or two high-pressure areas that would be created if the hole was designed into the piece. But even in these high-pressure areas, the pressure is well within the loads that the material can support, and Mahoney signs off the drawing. Now his design is accessible to any other designer, merely by calling it up on the designer’s own computer terminal. And if that designer has some problem with Mahoney’s design, some interference for example, he can take it right back to Mahoney there and then, rather than find out many months later. Says Mahoney: “The old ‘throw it over the wall’ business of ‘Here’s what I insist being the case, now do what you can with it,’ that’s gone away. But in order to really make it go away you still wind up throwing it over the wall. You just have to accept it being thrown back, that’s the difference.”

Now that Mahoney has told the computer that the design is complete, the piece is then incorporated in the computer’s memory. He can now look at the piece in its correct position in the door, highlighted to make it stand
out from the mass of other colored lines that now surround it. He can then zoom back to show the whole door on the screen, complete with the handle that fits into his component. He can move the handle and open the door. He can also zoom out farther, seeing the door in its correct position in the fuselage as it opens and closes. He can view it from above, so that he is looking down on the top edge of the door, or from inside, so that he can see some of the other components that are in contact with the piece. He can check to see whether the new design leads to any interferences that were not there before he made the change.

As he zooms out farther, he sees more of the whole plane, with other doors along the side of the fuselage, until the whole plane is visible, from tail to cockpit. Of course, as the plane gets smaller, some of the detail is removed; otherwise the amount of redrawing as more and more components came into view would slow things down. But it’s all there somewhere, stored in mainframe computers at Boeing’s Bellevue offices. And while Mahoney is looking at his door pieces, other designers will be using the same computers to draw or alter their own components, perhaps at the other end of the plane.

These miraculous events are made possible by two linked computer systems: CATIA—Computer-graphics Aided Three-dimensional Interactive Application—and EPIC—Electronic Preassembly in the Computer—which allow the different components to be designed and integrated into one vast computer simulation of the whole plane. Boeing started using a computer design system in 1978, for some parts of some aircraft. When they designed a wing strut for the 767 using this system, they found that it halved the number of changes they would have expected to make during manufacture. It was decided that the 777 would be the first plane to be fully built without mock-ups, entirely on the basis of 3-D computerized data. The system used is a Dassault/IBM program. Boeing had introduced CATIA in 1986. Then, when the 777 decision was made, Boeing computing staff devised the add-on program, EPIC, to allow the system to replace mock-ups entirely. The company distributed 2,200 computer terminals among the 777 design team, all of them connected to the world’s largest grouping of IBM mainframe computers, eight of them, at Bellevue, on the eastern shore of Lake Washington. In addition, other key participants in the process, from airframe manufacturers in Japan to engine-makers in America and the U.K., had immediate access to the data and were made aware of updates and changes as soon as they were confirmed.

Dick Johnson identified one particular benefit of this system compared with the old system using mock-ups: “With the mock-ups we had the three classes: class 1, class 2, and class 3. The engineer had three opportunities at three levels of detail to check his parts, and nothing in between. With CATIA he can do it day in and day out over the whole development of the airplane, and so it’s a tremendous advantage.”

Of course, this apparently limitless freedom to tinker with the design until the part is finalized could solve one problem by replacing it with another, as Johnson explained: “As we go through the process of designing day in and day out, people continue to change their designs and they will interfere with other parts. But they have a tool to find it now, whereas in the past we had no idea until we tried to build an airplane. You may have checked against somebody else’s part the day before, and when you check against it today, he’s changed his part and it goes right through your part. What we’ve done to try to help with that problem is to establish what we call a series of stages. There’s six stages to the design process. In each stage the design is going to change daily. And designers just have to deal with the fact that parts are changing and they have to coordinate with each other as best they can. But at the end of each of these six stages, we go through what we call a freeze. I say, ‘OK, no more designs.’ Now go work out all the remaining fit problems. So you get a few days where nobody is designing anymore. All they’re doing is comparing their designs with everybody else’s design to make sure they have no more interferences. Interferences that exist they take action to go and fix. So it’s a period in which people stop designing and do the fit check. Then they go back to designing at the end of the stage.”

The negotiating that had to go on between designers whose parts interfered led to all sorts of interactions between people who wouldn’t normally have any reason to meet, and sometimes found difficulty doing so, as Alan Mulally reported one day: “I saw one of our senior Structures people going up and down the 10-18 Building the other day looking for a hydraulic guy. He wanted to put a bracket on his floor beam, and they had not come to an agreement on where that bracket was going to go on the floor beam, or how big it was going to be and whether it was going to create an interference. And he stopped me in the hall and he was so mad because he couldn’t find the hydraulics engineer. And he said: ‘What do they look like? Do they have tubes in their pockets? Do they have tubes coming out of their heads? What do those people look like?’”

The main interferences were where one piece overlapped with another. But there are subtler and more complicated problems that can arise when a three-dimensional aircraft is designed on two-dimensional paper. For example, some components in the plane have to be removable for maintenance purposes. Steve Johnson is one of the designers responsible for parts of the
THE WING AREA CONTAINING THE TORQUE TUBE

wings. Inside each wing is a long cylindrical component called a torque tube: "We've had a situation in the wing trailing edge where all of the simple interferences were worked. We had a torque tube that fitted within the wing trailing edge and everything was OK. And then we found out through further analysis that we couldn't get the torque tube in, and we couldn't get it out. So we've had to go back and look at the 'swept volume'—the space that this torque tube needs around it so that it can be removed. It's really saved the company much money. Usually, you don't find these things out until the first airplanes are built or till somebody tries to service them."

EPIC was intended to have a further benefit, by creating a more direct link between the design of the components and the engineering processes that were to manufacture them. In modern airplane production, design and manufacture are generally two entirely separate activities. In the Boeing Company in 1992 the separation of the two was embodied physically in the distances between the manufacturing and assembly areas and the offices of the designers and engineers. Communication was often by internal post as designers released their hitherto jealously guarded drawings to the people who were going to make the plane, who might be several miles away. Their task was then to look at the particular component and consider the materials involved, the intricacy of the design, the forces it had to support, and the date it would be needed and come up with a way of manufacturing it. When a solid mock-up was involved, the part would often be handcrafted in one of the Boeing machine shops and then the design tinkered with until it was right. Then if it was a metal part of some complexity, the 3-D solid part would be used to design a production tool that would make it in quantity.

The 777 was to have tools of some sophistication. In addition to the conventional drilling, riveting, and milling machines that would be used to shape and connect the pieces of metal that made up the plane, there were more complex pieces of equipment, some of them costing hundreds of thousands of dollars, that simplified and streamlined the task of assembling multipart components of the plane such as the wing.

Some of these machine tools filled half a factory. The wing spars, for example, which were to be the first pieces of the plane to be manufactured, would be assembled in a 200-foot-long device, called the ASAT tool, that consisted of a framework to hold the components and an automated carriage to move along and connect them in sequence and according to computerized specifications. There were two main types of components to be connected in this tool. There were the spars, each as long as a wing, to be made 30 miles from the design offices, in Auburn, and the ribs, to be made 3,000 miles away, in Japan. These components would meet for the first time in the production tool and be expected to fit together, using three different types of fastener through thousands of holes drilled in the places the designers specified.

With the introduction of the EPIC system there could now be a direct link between the computer description of the design of a component and the instructions that a machine tool would need to make it. The tool has to know the size of the components, the breadth of the spar as it varies along the length, and the thickness of the pieces that are connected to the spars—upper cord and the webs and the stiffeners—which are also variable. For the first time in a Boeing plane, there was to be a direct—electronic—connection between the decisions made by the designers about the dimensions of a component and the data that the tool would need to put the pieces together.

But there was a further innovation that would be essential to ensure the success of this new tool. The link must not be solely electronic. Like the engineer Mulally saw in a corridor, each of the many parties involved in the 777 must be made to meet other species of engineer face-to-face to exchange ideas about matters of mutual interest. The time was past when de-
signers could “throw stuff over the wall” and wash their hands of it. This realization was what led the Boeing senior managers to develop two linked ideas, one called Working Together and the other, which they had come across in Japan, called design-build teams.

Working Together is a will-o’-the-wisp idea that evaporates if you think too hard about it, but seemed to have a fierce power to inspire men, and the few women, who worked on the 777. At one extreme you have Alan Mulally at his most mystical describing what are for him the roots of the Working Together philosophy: “I think the human spirit is a fabulous thing and I think there are beautiful butterflies in all of us and I think that we come with no baggage and no burdens and no limitations in our own minds and I think the environment we’re trying to create is that we have a shared thought, a shared vision, a shared appreciation, a shared understanding of what it is we’re really going to try to accomplish together. We would work out what each of us is going to do to use our unique talents to contribute. Then we’d know where we are. We’d know what needs special attention and we’d all bind together to help each other be a success.”

At the other extreme you have Ron Ostrowski, as down-to-earth as Mulally is ebullient, also a very senior engineer, suggesting how he came to understand, to accept, and then wholeheartedly to embrace the philosophy: “It was a point of conflict to begin with. You know, an engineer with pride wants to find a solution to his problems. And it’s not a natural thing to go out and explore publicly the particular problems you have. You’d like to be able to handle those yourself. So I’d say there was resistance at first, but it’s interesting how attention can be given to a particular problem like that, a communication problem if you will, by just making it OK to do that sort of thing, to express your problems, get all the help you can. If you’re working together, you’re going to find that a great assistance in finding the solution because none of us singly can do nearly as well as we can as a group. And so I think over the years that resistance has gone away. We shout it from the rooftops, in our program reviews with large audiences, in our all-team meeting. The same words have been used: ‘It’s OK,’ it’s almost like ‘Celebrate our problems,’ get them out in the open so we can go work them. So I think it’s come a long way, and I don’t think the resistance is there nearly so much anymore, and it’s overcome fairly easily. First of all, you get a lot of folks that want to work that way, and the more people you get involved with that kind of an attitude, the easier it is to break down the barriers of the few that don’t. And so it just kind of feeds upon itself.”

Working Together was to be the name of the first 777; it was to be painted on banners that went up around the factories, and on posters, baseball caps, badges, and T-shirts. And it was to be repeated as a mantra in speeches and discussions between Boeing and its customers and contractors. But there was a lot riding on it. Boeing believed in 1992, in an almost theological way, that this new way of working—whatever it was—could actually make a difference to the testable and costable quality of the plane they were making, an outcome that would not become apparent for another year, if not two. But observing it in action in the new type of meetings that were happening every day in every 777 department revealed a very different atmosphere from that conveyed in a story from earlier Boeing days. In the late 1950s there was a senior Boeing production manager named Howard “Bud” Hurst:

Hurst had told one of his machinists the way he was drilling holes was unsafe. For several days Bud kept watching him and noticed he was still drilling the same way. Hurst went to the worker’s foreman. “Straighten that guy out,” he ordered.

That didn’t accomplish anything either. Hurst brought the matter up at a production staff meeting and was told, “The man’s one of our best workers, he wouldn’t hurt himself, and besides you can’t tell him anything.”

The next day, Hurst approached the errant machinist.

“You gonna do that drilling the right way?” he asked.

The worker gave him the well-known freeway salute, and Hurst decked him with one punch.”*

Now if only he’d told the machinist that he had a beautiful butterfly inside him.

* Serling, Legend and Legacy, p. 169.