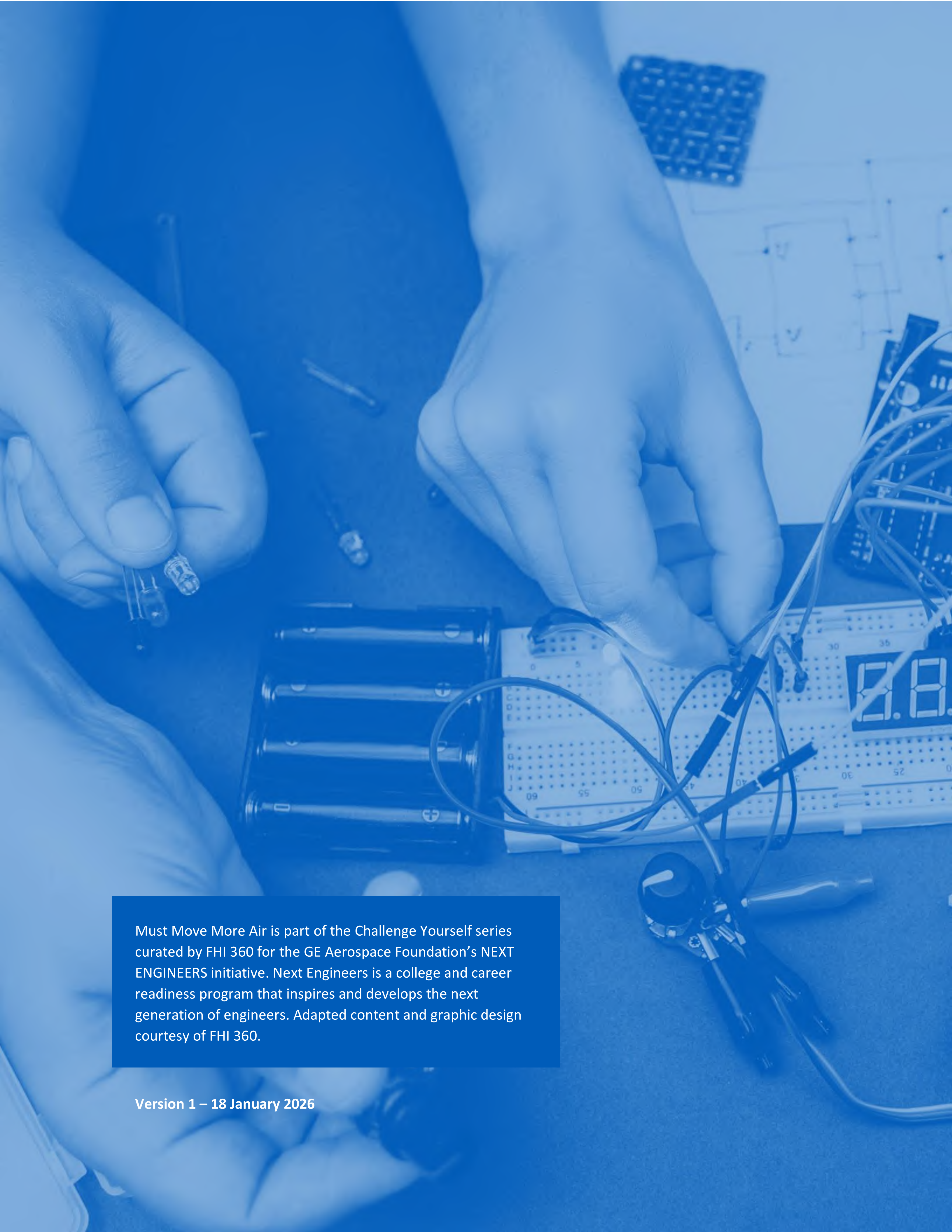
NEXT ENGINEERS

CHALLENGE YOURSELF

Extreme Machine Part 2: Must Move More Air

Aeronautical Engineering

NEXT ENGINEERS



Must Move More Air is part of the Challenge Yourself series curated by FHI 360 for the GE Aerospace Foundation's NEXT ENGINEERS initiative. Next Engineers is a college and career readiness program that inspires and develops the next generation of engineers. Adapted content and graphic design courtesy of FHI 360.

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Extreme Machine Part 2: Must Move More Air

NERD OUT

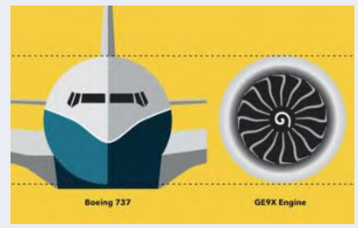
Getting Bigger

We noted in Part 1 that turbofans are very efficient jet engines and that the greater the bypass ratio, or BPR (the ratio of air bypassing the core to that going through the core), the more efficient and powerful the engine becomes. So, if increasing the BPR increases the engine efficiency and power, and increasing the engine size increases the BPR, engineers should just keep making bigger and bigger engines, right? Well, they have and they do, to a point!

If you look at a modern turbofan engine and an older one side by side, the difference is obvious. Modern engines are enormous and have enormous fans, creating bypass ratios of 10:1 to 12:1. Some experimental ultra-high bypass designs are aiming at ratios of 15:1 to 17:1.

The GE9X from GE Aerospace, for example, has a fan diameter of 3.4 m (over 11ft), making it the largest (and most powerful) commercial aircraft engine ever.

The GE Aerospace GE9X turbofan
Image by GE Aerospace is used under fair use
https://www.geaerospace.com/news/articles/farnborough-airshow-people-product/where-ge9x-engine-goes-ge-team-follows



THE GE9X

The GE9X engine on the Boeing 777 is bigger than the Boeing 737 fuselage! The GE9X engine is also 4 times more powerful than those typically on the 737.

Learn more

To dive deeper into the GE9X engine, watch these videos:

- ***See inside the GE9X, GE's newest game-changer*** (2:42)
  https://www.youtube.com/watch?v=XEiWwRyq_9E
- ***GE9X - The World's Biggest Jet Engine*** (5:50)
  https://www.youtube.com/watch?v=ZitKUqYDh1w
- ***World's Biggest Jet Engine Begun Rolling Off the Production Line for 777X*** (4:59)
  https://www.youtube.com/watch?v=Rg4fEpFb4a0
- ***This NEW GE9X Engine is Coming & Will Revolutionize the Industry!*** (13:27)
  https://www.youtube.com/watch?v=vESkwtx0Xxc

Why More Bypass Means Better Efficiency

We know that increasing the BPR increases the engine's efficiency, but why is this the case? To produce thrust, an engine must push air backwards. There are basically two ways to do this:

- Push a smaller amount of air faster
- Push a larger amount of air more slowly

It turns out that the second option is more efficient. Pushing lots of air gently wastes far less energy than blasting a small jet of air at high speed. This results in lower fuel burn, lower exhaust velocity, and less noise and is why modern turbofans are far more efficient than early jet engines.

We can explain why the second option is more energy efficient by looking at the physics. Stay with me here.

Changing an object's motion (like moving a jet engine and aircraft forward) requires a change in that object's momentum. Momentum (p) is given by

$$p = mv$$

where

$$m = \text{the mass of the object}$$
$$v = \text{the velocity of the object}$$

Impulse (J), is defined as the change in momentum (e.g., making an object move faster). Therefore, impulse is given by

$$J = m\Delta v$$

where

$$\Delta v = \text{the change in velocity of the object}$$

If we doubled the mass and halved the change in velocity, we would still achieve the same impulse.

$$J = 2m \times \frac{1}{2}\Delta v$$

Now kinetic energy is given as

$$E_k = \frac{1}{2} m \Delta v^2$$

If we substitute our new mass ($2m$) and new change in velocity ($\frac{1}{2}\Delta v$) into this equation, we get

$$E_k = \frac{1}{2}(2m)\left(\frac{1}{2}\Delta v\right)^2 = \frac{1}{4} m \Delta v^2$$

What if we halved the mass and doubled the change in velocity to achieve the same impulse?

$$J = \frac{1}{2} m \times 2\Delta v$$

If we substitute our new mass ($\frac{1}{2}m$) and new change in velocity ($2\Delta v$) into the kinetic energy equation, we get

$$E_k = \frac{1}{2}\left(\frac{1}{2}m\right)(2\Delta v)^2 = m \Delta v^2$$

We can see that doubling the mass and halving the change in velocity lets us achieve the same impulse (or change in momentum) for a quarter of the energy than if we halved the mass and doubled the change in velocity. For our jet engine, that means pushing twice as much air half as fast is four times more energy efficient than pushing half as much air twice as fast.

To learn more about why engineers are always striving to make bigger engines watch the video called HOW DO JET ENGINES work and WHY do they get BIGGER (12:20) (https://www.youtube.com/watch?v=5kE9wxsxdfc).

As much as increasing engine size to increase the bypass ratio sounds like a great idea, making bigger engines with bigger fans comes with costs and creates all sorts of engineering problems, some of them extreme.

There are four primary trade-offs that need to be managed when trying to increase the size of turbofan engines and their fans.

Bigger Fans Mean Bigger Blades

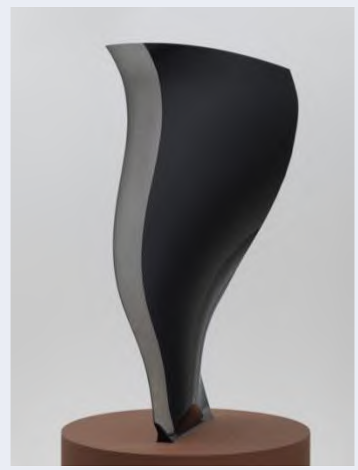
The force experienced by a spinning object like a fan blade (called the centripetal force) is given by

$$F = m\omega^2 r$$

where

$$m = \text{mass of the object}$$
$$\omega = \text{angular velocity (speed of rotation)}$$
$$r = \text{radius or distance of the object from the center of rotation}$$

Larger fans require larger blades. This increases the value of r and therefore the centripetal force. Making blades stronger usually means making them thicker. This increases their mass (m), again increasing the force. So, we need to slow the spinning (ω), but this reduces the amount of bypass airflow, defeating the reason for the bigger fan in the first place.



BEAUTIFULLY ENGINEERED

The fan blades from the GE90 engine are so beautifully designed and manufactured that one of them is part of the New York Museum of Modern Art's collection.

Read more

As the centripetal force increases, we also need a stronger fan hub and a thicker, stronger engine casing to contain the bigger blades if one ever breaks apart. This all adds more material and hence, more mass. More mass reduces aircraft performance and increases costs.

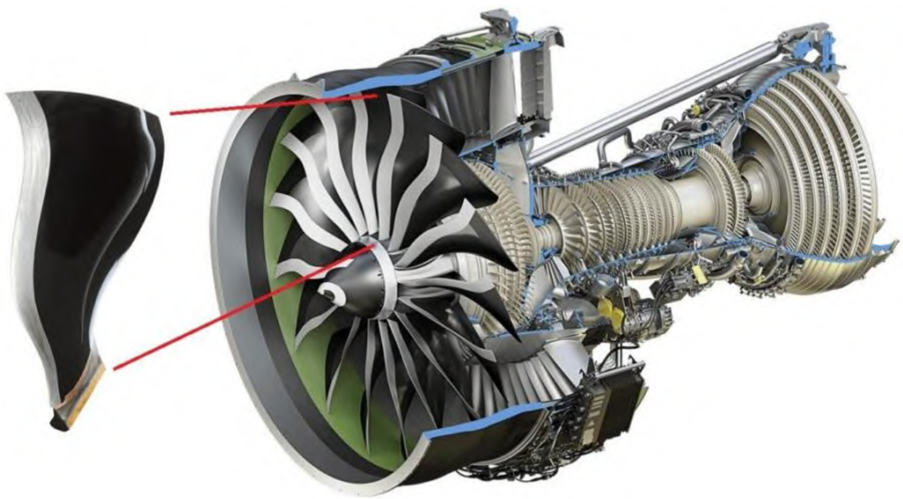


Illustration of the GE9X fan and blades
Image by GE Aerospace is used under fair use
https://ozkancengiz.com/the-record-breaking-engine-ge9x/

GE Aerospace engineers addressed this by making the blades much stronger but also lighter and thinner by manufacturing them out of carbon-fiber composite. Each blade is made from about 1,700 sheets of carbon fiber impregnated with a very strong and durable resin and then cured at high temperature and pressure.

Learn more about these carbon-fiber composite fan blades by watching the video called [GE90 and GEnx Composite fan blades](https://www.youtube.com/watch?v=eoNySabChvA) (7:06) (https://www.youtube.com/watch?v=eoNySabChvA).
Then watch the video called [GE9X: Testing the Composite Fan Blades](https://www.youtube.com/watch?v=jwqNIh-Fwpc) (2:39) (https://www.youtube.com/watch?v=jwqNIh-Fwpc) to see how they test these blades to make sure they can withstand the enormous stresses they are routinely placed under as well as incidents like bird strikes.

Bigger Fans Increase Drag

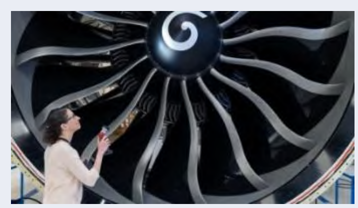
A bigger engine with a bigger fan is a wider engine, which creates more aerodynamic drag. Increased drag increases fuel burn.

GE Aerospace engineers addressed the problem of drag in 2 ways. Firstly, they redesigned the fan blades using advanced 3D modelling to have a complicated 3D swept shape. This improved the aerodynamics and operation of the blades. This also allowed them to successively reduce the number of blades in newer engines.

Having fewer blades with the swept design reduces drag and weight. This improves the airflow and reduces overall turbulence, so each blade processes more air with less waste. It also lowers the "aerodynamic interference" between adjacent blades, enabling wider spacing without losing efficiency and allows the fan to spin faster and move air more quickly without the normal energy costs.

DO THE MATH

We use $F_c = m\omega^2 r$ to calculate centripetal force. A GE9X fan has a radius of 1.7 m, spins at 2,510 RPM at take-off, with each blade weighing about 25 kg. This means that each blade experiences a centripetal force of about 2,900,000 N. That is equivalent to the weight of a Boeing 747! On each one of the 16 blades!



A PRETTY PENNY

Each of the 16 fan blades in the GE9X can cost up to US$100,000.

Secondly, they also carefully designed the nacelle (the engine's outer casing). This included manufacturing it out of lighter and stronger composite materials and redesigning the lip to reduce drag and improve airflow into the engine.

The lip of the GE9X nacelle
Image by GE Aerospace is used under fair use
https://www.popsci.com/story/technology/ge9x-biggest-jet-engine-explained/

Bigger Fans Are Harder to Spin

Large fans need enormous **torque,** or turning force, to make them spin. This energy needs to be generated by the turbine. The more energy used to turn the fan, the more fuel needs to be burnt, or the less energy is available to the rest of the engine or for thrust. This increased torque also adds stress to shafts, bearings, and gears.

The GE9X Low Pressure Turbine
Image by Avio Aero is used under fair use
https://www.avioaero.com/news/articles/avio-aero-goes-for-the-double

FEWER AND FEWER

GE Aerospace engineers have used fewer and fewer fan blades in their commercial jet engines over the years.

- The GE90 fan has **22 blades** (down from 38 in earlier engines).
- The GEnx fan has **18 blades**.
- The GE9X fan has just **16 blades**.

GE Aerospace engineers addressed this challenge by designing a highly efficient 3-stage low pressure turbine for the GE9X. Reducing the number and mass of the fan blades also helps to reduce the torque required.

To learn more about this low pressure turbine watch the video called GE9X: Refining and Testing the Low-Pressure Turbine (LPT) (2:37) (https://www.youtube.com/watch?v=4dAIoefe0_Q).

Bigger Engines Are Just Bigger

Bigger engines create integration problems with the aircraft they are design to propel. Ground clearance limits how large engines can be. Wings must be redesigned to carry heavier engines. Airports and maintenance equipment must adapt.

GE Aerospace engineers dealt with this challenge by mounting the engine forward and higher on the wing. With the GE9X, they also tilted the front of the engine up by 7 degrees. Boeing also made the landing gear of the 777X taller.

Engine design does not happen in isolation—it affects the entire aircraft.

THE HAMSTER POUCH

The CFM56 engine used on the Boeing 737-400 has a very distinctive flattened bottom to create the needed ground clearance, earning it the nickname of the “hamster pouch”.

Engineering Trade-offs

GE Aerospace engines like the GE90, GEnx, and GE9X pushed bypass ratios higher with each generation, but never blindly. Increasing the bypass ratio improves fuel efficiency, increases thrust and performance, and reduces noise. But it also increases size, weight, and complexity and raises manufacturing and maintenance costs.

Therefore, each design decision reflects careful choices about:

- Fan diameter
- Materials cost
- Manufacturing costs
- Noise limits
- Long-term durability
- Airline operating economics

There is no single “best” bypass ratio – only the best compromise for a given aircraft and mission. A slightly smaller fan that lasts longer and costs less may be a better engineering solution than the biggest possible fan.

One of the hardest skills in engineering is knowing when to stop, when not to optimize further. The goal cannot simply be the highest bypass ratio. The goal must be the best overall system for the given circumstance.

In the next article, we’ll move from the outside of the engine to the first part of the core to discover how engineers compress the air to extreme pressures.