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HOW FAST CAN EVANGELION RUN? APPLICATION OF AERODYNAMICS AND SCALING LAWS TO THE SUPER ROBOT

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ABSTRACT

Super robots are huge, powerful robots that protect mankind from various invaders, and thus these superheroes are the main figures in many science fiction movies and Japanese animations. Among them, Evangelions have been a very popular type of super robot since the 1990s given that the animation series Neon Genesis Evangelion has been globally influential in various pop cultures. Evangelions (also called Evas) are cyborgs comprised of huge human body and robotic systems, and in the animation series, they often run at seemingly high speeds, which is quite different from traditional super robots. In this paper, we attempt to estimate the running speed of Evangelions based on known scientific facts. First, we measured the running speed of Eva Unit 01 (Eva-01) to be between 910 and 980 m/s based on its step length measured in movie scenes, and the Mach cone formed behind Eva-01. Second, we employed scaling laws known for animals and find that the maximum running speed of Eva-01 is 0.9 m/s. This striking difference between the anime-based speed and the physics-based speed raises a question as to how Eva-01 can run at such a high speed, and we conjecture that the cyborg can do so due to internally stored electrical power.

PROLOGUE

When an Angel, a mysterious invader, falls from the outer space to the ground, Eva Unit 01 (or Eva-01) a gigantic cyborg, has to sprint to reach the touchdown point of the Angel in order to be able to defeat the invader. As Eva-01 continues to accelerate, this 80 m-tall superhero striving to protect mankind from the Angel breaks the sound barrier, and maintains a speed faster than sound, thus generating shock waves.

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Is it really possible for Eva-01 to run this fast? How fast can Eva-01 actually run? We attempt to answer these questions using scaling laws for animals.

INTRODUCTION

Super robots are gigantic robots protecting mankind and Earth from various invaders and evil beings, and thus they can also be categorized as superheroes [1]. Super robots have been the principal figures of various animations, TV series, and science fiction (SF) movies, including Robot Taekwon V, Mazinger Z, Voltron, the Autobots in Transformers, and Jaegers in Pacific Rim. Often these super robots run (yes, they can run despite their size and weight) to chase their enemies or to escape from dangers, in a way similar to how humans run. However, it is questionable whether it is physically possible for super robots to run. There are already real two-legged robots that can run like humans, such as Boston Dynamic's Atlas (height: 1.5 m, weight: 80 kg, speed: 1.5 m/s) [2]. Therefore, someday we (humans) might be able to see and experience real super robots, such as Jaegers, which can also run.

Thus the key question is: how fast can these super robots run? In this paper we attempt to estimate the maximum running speed of Eva-01, one of the most globally known super robots, by referring to known scaling laws.

Neon Genesis Evangelion was one of the most revolutionary Japanese animation series (Anime) in the 1990s, and it is still influential in various types of popular culture [3]. In a nutshell, the animation describes the struggles of mankind (in particular the inhabitants of Tokyo-3) against Angels, a group of mysterious invaders. If an Angel encounters Adam, the first Angel that mankind encountered, Third Impact would occur and be devastating for mankind and Earth. Thus, Evangelions, or Evas, were created to neutralise the threat from Angels. Eva Unit 01 (Eva-01) is a gigantic cyborg-type super robot that is actually an artificial human giant with embedded robotic systems (see Figure 1(a)).

Through the series of Neon Genesis Evangelion, several scenes show that Evas have fingernails, skin, eyes, muscle, a mouth, and blood just as the human body does, and that the armour covering Evas is actually to restrain their power. This similarity between the human body and Evas opens up the possibility of applying scaling laws known for animals, such as humans, to Evas.

From the various versions of Neon Genesis Evangelion, we focus on the second movie in the recent Rebuild of Evangelion series: Evangelion 2.0:

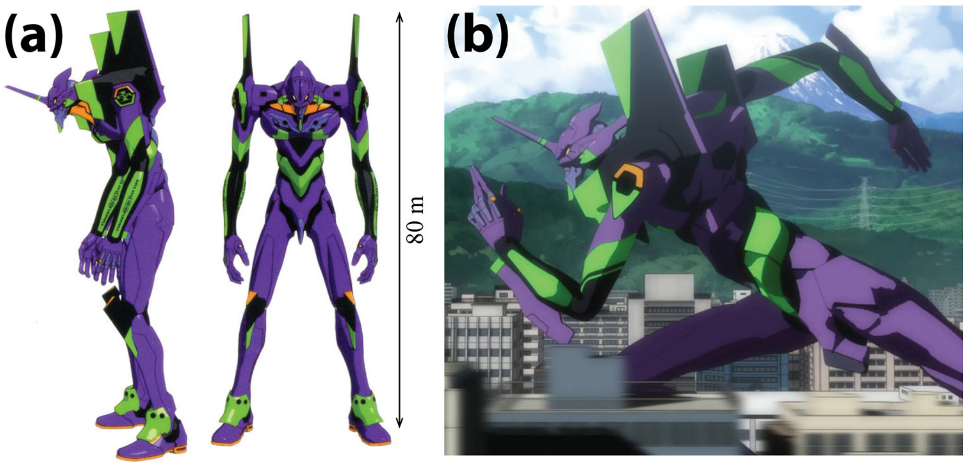

Figure 1: (a) Images of Eva-01. Reproduced from [4]. (b) Snapshot of Eva-01 running. This image was captured from [5].

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You Can (Not) Advance [5]. In this movie, the 8th Angel, named Sahaquiel in the TV series, falls from the outer space to invade Tokyo-3. Three Eva units have to reach the touchdown location of the Angel at the right time to defeat the Angel. However, Sahaquiel changes its trajectory by accelerating, so the Evas have to run (Figure 1(b)) as fast as they can to be in the right place at the right moment. As the Evas are about to miss Sahaquiel's touchdown location, Eva-01 suddenly starts accelerating further and breaks the sonic barrier, creating shock waves in the process. Fortunately, Eva-01 reaches the touchdown location on time and stops the Angel.

With this scene, we raise our eyebrows with regards to the realistic nature of the events. Is it really possible for Eva-01 to run at such a high speed, considering the mammoth size of Eva-01? What is the maximum running speed of Eva-01? Aerodynamically speaking, what happens to Eva-01 while it is running? In this article we attempt to answer these questions based on well-established aerodynamics about shock waves and scaling laws for animals.

MEASURING EVA-01'S RUNNING SPEED USING MOVIE SCENES

MEASUREMENT BASED ON STEP LENGTH

Before attempting to estimate the running speed (U) of Eva-01 based on scaling laws, we first measured it using the movie scenes. Figure 2(a) shows sequential images (two steps) of Eva-01 running on MABSS (Multipurpose Adjustable Blast Shield Structure) plates in Tokyo-3. Each step takes 5 frames, and the frame rate of the movie file is 24 frames per second (fps). Thus, each step takes about 0.21 s (about five steps in one second). From the scene, we observed that the step length of Eva-01 is about 1.2 times the width of the MABSS plate. So, it is possible to measure U by dividing the step length of Eva-01 with the time taken for one step. However, the width of one MABSS plate is unknown. We tried to estimate the width using the green building shown in Figure 2(a) as a scale reference. Assuming 30 metres (m) for the width of the green building (naïve assumption, but quite realistic), we calculated that the MABSS plate is 160 m wide, which appears reasonable considering that Eva-01 is 80 m tall (Figure 1(a)). Thus, the running speed (U) of Eva-01 is estimated to be 914 m/s (from the calculation 1.2 × 160 m / 0.21 s). This estimation seems relatively accurate given that the Eva-01 in the scene can run around a few large blocks of buildings in the mega city in a second.

Nevertheless, our measurement of U is puzzling since Eva-01 is running faster than the speed of sound. The speed of sound in air (c) is 340 m/s in conditions with atmospheric pressure and temperature, and when an object is moving faster than this speed, it creates shock waves in the air. This aerodynamic phenomenon can be predicted using the Mach number (Ma), which is defined as the ratio of the airflow speed (or the speed of a body moving in stationary air) to the speed of sound. In the case of Eva-01, Ma = U/c. For running humans, Ma is very low (the Ma of Usain Bolt is 0.03). For a running Eva-01, Ma is about 2.7, which indicates that the cyborg is running in the supersonic flow regime in which shock waves do exist [6]. However, surprisingly no shock waves are seen around Eva-01 in Figure 2(a).

It should be noted that the above estimation of U is essentially based on the assumed dimension of the green building in Figure 2(a). In other words, our assumption of 30 m for this scale reference may have led to an incorrect estimate of U, and thus an incorrect estimate of the Ma value for Eva-01.

To check the validity of our assumption, we reverse-calculated the dimension of the building given that no shock waves are shown in Figure 2(a). If Eva-01 is assumed to be running in the subsonic regime (i.e., Ma < 0.8 [6]), the green building would be 9 metres wide. This estimation is definitely unrealistic because it is too small for the multi-story building. Therefore, the bottom line is that Eva-01 is running in the supersonic regime.

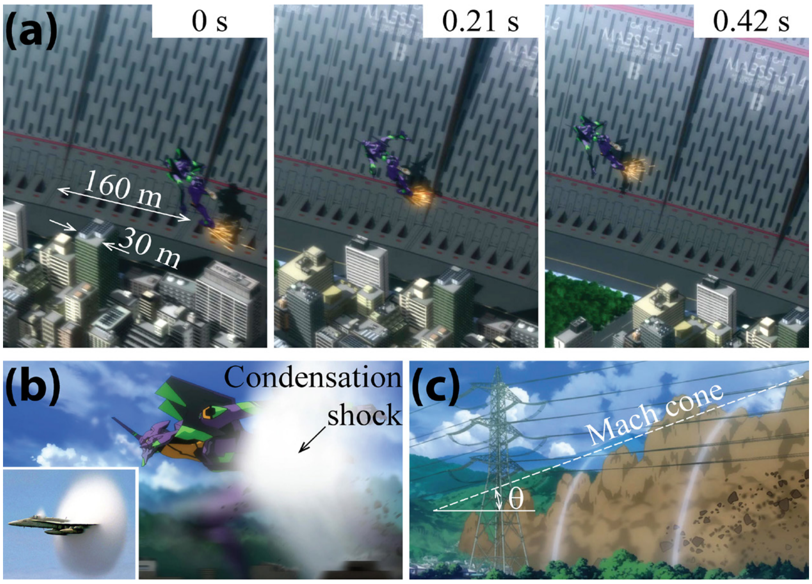

Figure 2: (a) Eva-01 running on MABSS (Multipurpose Adjustable Blast Shield Structure) plates. The width of one MABSS plate is measured based on the assumed size (30 metres) of the green building. (b) Condensation shock around Eva-01 passing through the speed of sound. Inset: Condensation shock around a F/A-18 Hornet jet fighter passing through the speed of sound [6, 7]. (c) Mach cone formed by running Eva-01. Images were captured from [5].

MEASUREMENT BASED ON MACH CONE

As the Angel Sahaquiel accelerates its descent towards the touchdown location, Eva-01 runs faster and faster, breaking the sound barrier in the process, and enters the supersonic regime. Figure 2(b) shows a condensation shock or vapour cone around Eva-01. Readers may have seen similar pictures showing the vapour cone formed around an airplane, such as the inset of Figure 2(b) [7]. In this picture, the F/A-18 Hornet airplane approached the speed of sound in air with moisture. The Ma of this airplane appears to be slightly lower than 1, but airflow around the aircraft could be locally supersonic. Thus, visible condensation shocks could be formed on such local locations of Ma > 1 [6]. Therefore, the condensation shock in Figure 2(b) shows that Eva-01 is running at Ma ≈ 1 and entering the supersonic flow regime, thus breaking the sonic barrier.

As Eva-01 further accelerates beyond the speed of sound, it creates shock waves in the air. In the scene from the movie, such effect is visualized by slowly growing white rings and explosively rising dusts as shown in Figure 2(c). Although it is unclear what these white rings are (they are created quite regularly behind Eva-01 while running and then slowly grow), it seems reasonable to assume that they are representations of shock waves (like the vapour cone in Figure 2(b)) or pressure waves. In the supersonic motion of Eva-01, these waves follow behind the cyborg and form a conical locus called the Mach cone as shown by the dashed line in Figure 2(c). The angle of the Mach cone (θ) is related with the Mach number of Eva-01 by the expression $\sin(\theta) = 1/\mathrm{Ma}$ [6]. From the slope of the dashed line in the image, $\sin(\theta)$ is estimated to be approximately 0.35, which infers that the Mach number of Eva-01 is 2.9, the equivalent of 971 m/s. This estimation is very close to our estimate of the running speed based on the step length measurement.

MEASURING EVA-01 RUNNING SPEED USING SCALING LAWS

SCALING LAW FOR BODY MASS

The analyses presented in the preceding section estimate a running speed for Eva-01 between 910 and 980 m/s. Next, we assessed if this speed range is feasible using a known scaling law between body mass and the maximum running speed of animals. It must be restated that Eva-01 is a cyborg-type super robot made of human-like body components and robotic systems. Hence, we assume that scaling law for animals can be applied to Evas.

A scaling law can be used to describe the relation of two measurements. For instance, the power law formula $M = aL^b$ can be used to relate body mass M to characteristic length dimension L for various organisms of different sizes. We will use the cube example shown in Figure 3(a) to find a general scaling law between the size and mass. In this example, the size of one cube is L. Then, the mass (M) of this cube is ρL^3 where ρ is the density of the cube. Now let's stack four cubes into a cube of side $2L$. Hence, the mass of the second cube is $\rho(2L)^3$. Finally, we stack nine cubes into a cube with the side length of $3L$, which leads to a mass of $\rho(3L)^3$ for the third cube. We can find a relationship between L and M such that $M \propto L^3$. M increases with L with the scaling exponent of 3 as plotted in Figure 3(b), and the slope between M and L in the log-log plot is 3 as shown in Figure 3(c). Thus, this scaling law becomes clear when presented on a log-log plot.

This scaling relationship between body mass and length is valid for human bodies. According to McMahon and Bonner, "the table complied by life-insurance companies showing the relation between height and weight in humans shows that body weight is generally proportional to height raised to a power of about 2.9," i.e., $M \propto L^{2.9}$ [8]. This scaling exponent is very close to the exponent of 3 found in the cube example.

BODY MASS OF EVA-01

Unfortunately, there is no official body mass information of Eva-01. Instead, it is known that Eva-01 is 80 m tall (Figure 1(a)) [4], which allows for an estimate of the body mass of Eva-01. Given that Eva-01 is a kind of scaled-up human, we opted to use the height and body mass data of humans. Eva-01 is slender, so we chose to scale from a 6 feet (= 1.83 m) tall human with a body mass index (BMI) of 19, making the body mass 140 lb (= 63.5 kg) [9]. As a result, the scaling relation of $M \propto L^{2.9}$ leads to a body mass of 3.64×10^6 kg for Eva-01.

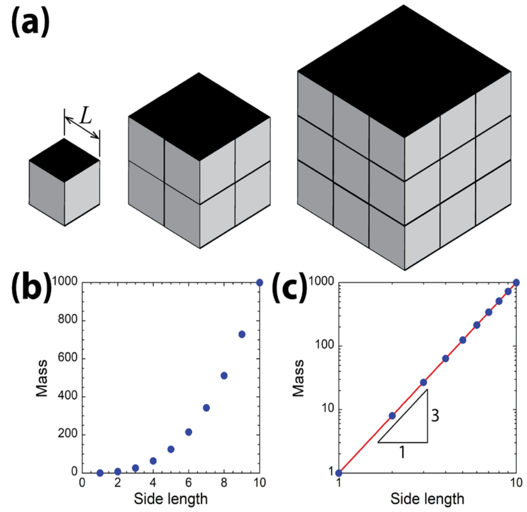

Figure 3: Cube example to find a scaling law between size and mass. (a) Cubes of different sizes. (b) Linear scale plot and (c) log scale plot between side length and mass. The density of the cube is assumed to be 1 for (b) and (c).

It should be noted that this body mass estimate is conservative as it excludes the armour and any internal machinery parts of Eva-01. Although conservative, our mass estimation suggests that Eva-01 is about 24 times the mass of the heaviest living animal: the blue whale which has a mass of more than 100 tons [10]. Blue whales can reach such a large mass as their huge body is supported by water (i.e., buoyancy). However on land, their body weight would crush their bones. In the same sense, our estimation suggests that the body weight of Eva-01 would break its legs even while it is just standing still. This may explain why there is no official body mass information of Eva-01.

SCALING LAW FOR RUNNING SPEED

Similar to the relation outlined between size and body mass (i.e., $M \propto L^3$), the maximum running speed and body mass of animals have been studied in terms of a power law relation (i.e., $U_{max} = aM^b$ where $b > 0$). This simple relationship suggests that larger animals are faster runners. However, it is very well known that the largest animals are not

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the fastest, as demonstrated by the fact that the fastest four-legged animal is the cheetah, and not the elephant. Therefore, the power law is limited in describing the observed relationship between U_{max} and M.

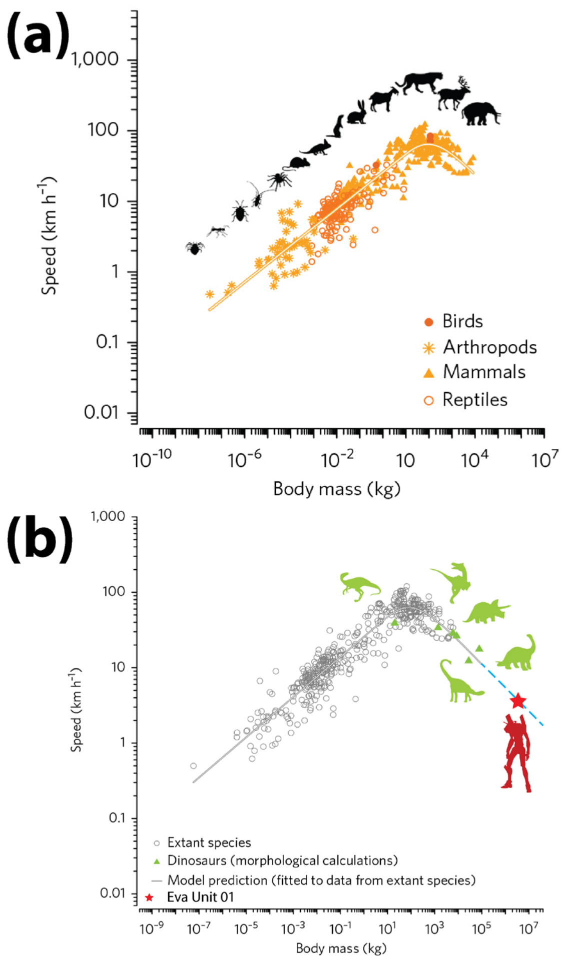

Figure 4: (a) Comparison between the scaling model of Hirt *et al.* and empirical maximum speed (U_{max}) data of running animals. (B) U_{max} estimation for extinct dinosaurs and Eva-01 using the scaling model of Hirt *et al.* Reproduced from [11].

Recently, Hirt *et al.* proposed the following general scaling model for the U_{max} of animals [11]: $U_{max} = aM^b[1 - \exp(-hM^i)]$, where a, b, h and i are curve fitting parameters. They considered that acceleration time is the critical factor that determines the U_{max} of animals due to restrictions on the quickly accessing available energy for acceleration. In their scaling model, the limiting term $[1 - \exp(-hM^i)]$ is close to 1 for small animals (i.e., small M), which means that small animals can run at U_{max} close to the theoretical maximum speed ($U_{max\_t} = aM^b$). This is because small to intermediate-sized animals have sufficient time to reach their U_{max_t} owing to their rapid acceleration. On the contrary, as the animal size increases (i.e., increasing M), the limiting term in the equation decreases and reduces U_{max}. In contrast to small animals, large animals cannot reach their U_{max_t} because they run out of readily available energy during their limited acceleration time before reaching U_{max_t}. Therefore, larger animals have a lower U_{max} than U_{max_t}.

Hirt *et al.* tested their scaling model by compiling available U_{max} data for running animals for a wide range of body mass and comparing them with their model. As Figure 4(a) shows, their scaling model can successfully replicate the known U_{max} values of animals for a wide range of M, and even capture the hump-shaped pattern of U_{max}. Hirt *et al.* determined the values of the coefficients of their model for running animals as follows: $a = 25.5$, $b = 0.26$, $h = 22$ and $i = -0.6$. Furthermore, their model agrees well with available U_{max} estimates of extinct dinosaurs (Figure 4(b)), which shows that the scaling model of Hirt *et al.* can be used for our purpose of estimating U_{max} for Eva-01.

HOW FAST CAN EVA-1 RUN?

As the simple power law of $U_{max\_t} = aM^b$ would estimate a value of U_{max} for Eva-01 that is too high given the cyborg's body mass, we used the scaling model of Hirt *et al.* Using $U_{max} = 25.5M^{0.26}[1 - \exp(-22M^{-0.6})]$, we estimate that U_{max} of Eva-01 is 3.3 km/h, which is about 0.9 m/s (Figure 4(b)). This estimation of U_{max} is smaller than the U value estimated from the movie scene by three orders of magnitude. Considering that Eva-01 is 80 m tall, furthermore, U_{max} of 0.9 m/s implies that it would take about one minute for Eva-01 to make one step (40 m / 0.9 m/s = 44 s), with the step length being assumed to be a half of the height. Thus, this estimation appears unrealistic.

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Here, we notice that the scaling model of Hirt *et al.* is based on one main observation that the quickly available energy of animals for acceleration is limited. This observation is true for animals that must convert biochemical materials (adenosine triphosphate (ATP)) stored in the body for muscle motion. However, this observation is not applicable to Eva-01. Evas are supplied with external electrical power through the umbilical cable or cord, and when they are detached from the power cable, they can move for up to five minutes relying on the internal battery. This means that the sprinting of Eva-01 is not limited by the quickly accessible energy. As such, we re-estimate the U_{max} of Eva-01 using $U_{max} = 25.5M^{0.26}$ without the limiting term, which is U_{max_t}, and it is 1,295 km/h (= 359.7 m/s). This new estimation is the same order of magnitude of U as measured from the movie scene.

USING ANIME FOR STEM EDUCATION

This paper is based on one of the first author's "Professor Otaku" lectures in which the concepts of science and engineering are explained based on examples found in Anime. Movies and TV shows generally, Anime specifically, provide countless engaging examples that can be used to illustrate and teach science and engineering concepts. Examples from Anime and other movies and TV shows have several advantages over traditional textbook-style examples. First, these types of non-traditional examples can pique students' interest more than standard textbook descriptions and illustrations. Second, if an example video clip can be shown in class, the teacher can anchor the lesson in that shared experience, ensuring that all students understand exactly what is portrayed in the example, which can be difficult when static textbook pages are used to try to convey motion. Third, sourcing examples from movies and TV shows can help grow the student-teacher relationship by highlighting common interests and connecting over non-academic topics. Finally, fictional examples allow for instruction to be framed with a different sort of question, such as, "did the creator adhere to the laws of physics in portraying this action?" or "could this really happen?"

Recently, we suggested using Studio Ghibli's Castle in the Sky to explain fluid mechanics concepts such as buoyancy, drag and lift force, and terminal speed of a freely falling body [12]. Similarly, our present speed estimation of Eva-01 based on the condensation shock and Mach cone (Figure 2 (b), (c)) can help with explaining basic concepts in compressible fluid dynamics, such as the speed of sound, shock wave, and the Mach number. Also, our maximum speed estimation of Eva-01 based on the scaling law (Figure 4) can be used for introducing concepts of scaling laws. Other scaling laws for animals, such as scaling laws of skeletal mass, heat production and oxygen consumption rate on body mass [8, 10], can be applied to Eva-01 to judge the feasibility of the cyborg in the real world, which will be an intriguing way to practice scaling laws and appreciate the physical meaning of the scaling law. These examples can be employed not only in the formal teaching of physics, biomechanics and fluid mechanics, but also in informal STEM (science, technology, engineering and mathematics) outreach activities aimed at the general public.

It is not uncommon to see STEM outreach programs resort to creative content from pop culture resources to increase public engagement across all ages. Take the 2018 example of a computer science curriculum for middle school STEM camps that linked a Mission to Mars with computer science [13]. The focus of this curriculum was to introduce computational thinking skills to 5th and 6th graders. On a wider scale, in 2013, the Phoenix ComiCon (PCC) experimented with including science discussion panels [14]. It became so popular that they needed to expand the track the following year. Panellists included STEM outreach specialists, early career scientists, and industry specialists amongst others. Topics ranged from artificial intelligence to space exploration and biotechnology with a focus on pop culture linkages. Internationally, a group of engineering students at the Texas A&M University

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at Qatar collaborated with their professor on writing a children's book with Anime style characters [15]. Benefits to both the students creating the book and children reading it were catalogued. Regardless of age and borders, it is intellectually stimulating to apply known scientific facts to fictional situations and figures in Anime.

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