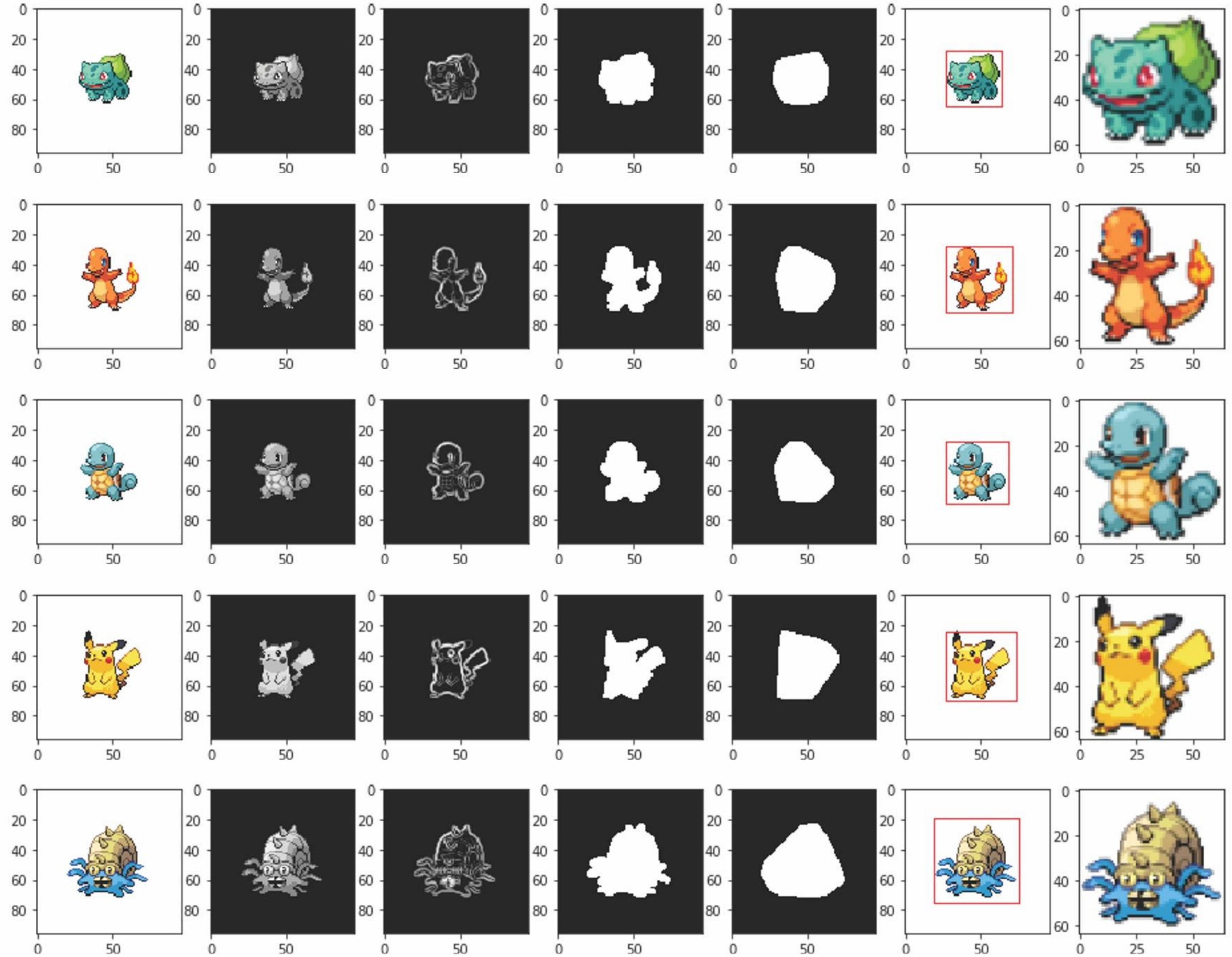
Journal of Geek Studies

Vol. 4(1). 2017.



ISSN 2359-3024

Journal of Geek Studies

The Journal of Geek Studies is a non-peer-reviewed, open-access, non-profit, online biannual publication devoted to the popularization of science.

Journal of Geek Studies
http://jgeekstudies.wordpress.com/
http://jgeekstudies.org /

ISSN: 2359-3024 (online).
Vol. 1 (2014) – present.
São Paulo, SP, Brazil.

1. Science; 2. Technology; 3. Geek Culture.

Cover art: Examples from the sprite centering pipeline used in the article by Henrique M. Soares, featuring five Pokémon (The Pokémon Company, 1996–2017): Bulbasaur, Charmander, Squirtle, Pikachu and Lord Helix. See the full article in this volume for an extended explanation.

Journal of Geek Studies

ISSN 2359-3024

Frankenstein, or the beauty and terror of science

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In January 2018, it will be two hundred years ago that Mary Shelley's gothic novel *Frankenstein; or the Modern Prometheus* was first published. However, international commemorations have already started and the so-called Frankenstein Bicentennial Project has been launched by Arizona State University. Instead of awaiting the bicentenary of the first *publication*, meetings have been organized to celebrate the famous occasion on which the idea of the novel was first *conceived* by Mary Shelley (then still Mary Godwin). That was during a memorable nightmare in the early hours of June 16, 1816, while she was staying in a villa on the shores of Lake Geneva. In mid-June 2016, therefore, an international workshop entitled 'Frankenstein's Shadow' was held in Geneva to commemorate this event and to determine the contemporary relevance of Mary's novel for understanding and assessing new developments in the modern life sciences. After all, in many contemporary debates references to her horror story are still routinely being made. Genetically modified crops, for instance, are often condemned as 'Frankenfoods' and life science researchers are frequently accused of *hubris* or *attempting to play God*, just as Mary's protagonist Victor Frankenstein supposedly did. Indeed, the mere mentioning of his name readily brings to mind such associations among laypersons, or as Marilyn Butler writes, "Readers, filmgoers, people who are neither, take the very word Frankenstein to convey an awful warning: don't usurp God's prerogative in the Creation-game, or don't get too clever with technology" (Butler 1993: 302).

A WET, UNGENIAL SUMMER

The circumstances in which Mary first conceived the idea of her novel may help to illuminate the significance and meaning of her literary creation. In the late spring of 1816 a remarkable entourage, next to Mary Godwin, assembled on the shores of Lake Geneva: the romantic poets Lord Byron and Percy Shelley (Mary's lover and later husband), Mary's step-sister Claire and doctor John William Polidori. The then 28-year-old Byron was the oldest of the company; Mary was still only 18, but had already lost her first child as an unmarried teenage mother. It was a time, just after Napoleon's defeat, that British citizens could again freely travel through Europe. Each of the participants had their own reasons to flee from the United Kingdom. Byron was haunted by creditors and scandals. Percy Shelley had abandoned his wife and child and made himself unpopular through his overt atheism. Claire had persuaded Percy and Mary to follow Byron in his travels, because she had a crush on the noble poet (her attempt to win his love would however be in vain). Young doctor Polidori had been recruited by Byron to be his travel companion and private physician, but also cherished literary ambitions himself (in 1819 Polidori would publish *The Vampyre: A Tale*, another product of the Geneva 1816 summer and a source of inspiration for Bram Stoker's *Dracula*). The choice of Geneva as the place to stay had been partly inspired by Jean-Jacques Rousseau, the proud "citizen of Geneva". In the footsteps of their romantic precursor, Byron and Percy Shelley wanted to experience the majestic sublimity of the natural landscape around Geneva. In the nearby hamlet of Cologny, Byron had rented a spacious residence, Villa Diodati; Percy and Mary stayed with Claire at a more modest dwelling in the neighbourhood, but regularly visited Byron to spend days and evenings at his villa.

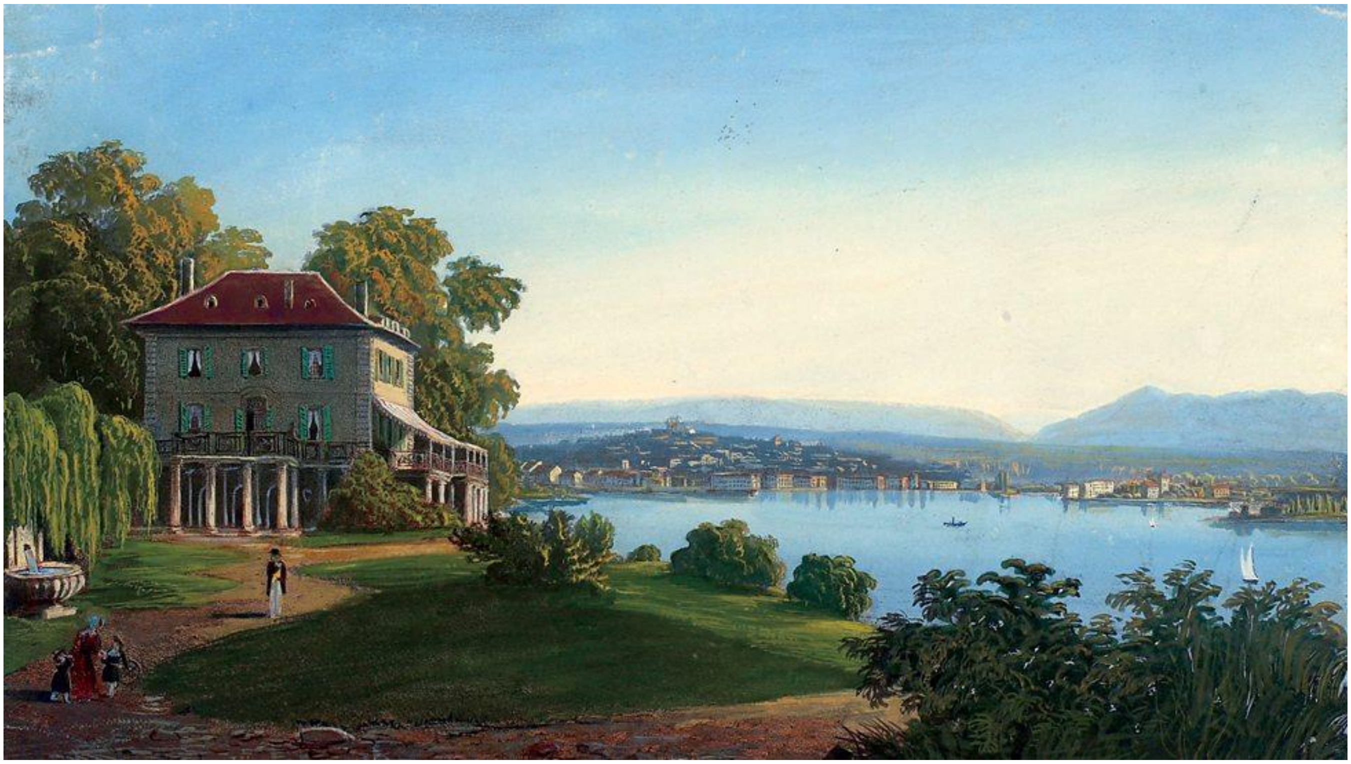

Figure 1. Villa Diodati on the shores of Lake Geneva. Painted by Jean Dubois. Image extracted from Wikimedia Commons.

It appeared as if the summer of 1816 did not want to become a real summer. In the introduction to the revised 1831 edition of her novel, Mary looked back: "But it proved a wet, ungenial summer, and incessant rain often confined us for days to the house." (Shelley, 2003 [1831]: 6–7). Incidentally, this was not a purely local weather condition. In North America, the year 1816 would even go down in history as "the year without summer". We know now that these meteorological abnormalities had to do with the most violent volcanic eruption of the last one thousand years, to wit, the eruption of the Tambora on the Indonesian island of Sumbawa in April 1815. The enormous amounts of volcanic ash spread throughout the earthly atmosphere massively reflected sunlight and disturbed global weather processes for three years in a row (D'Arcy Wood, 2014).

Figure 2. Possible depiction of the eruption of Mount Tambora on Sumbawa in 1815. Author unknown; image extracted from Scientific American Blog Network (2012).

Confined by incessant bad weather and illuminated by candlelight, Byron and his guests at Villa Diodati tried to keep boredom at bay by reading ghost stories to each other. At some moment Byron proposed a kind of contest in which each of the participants had to come up with a ghost story of their own. Mary accepted the challenge, but was not immediately able to think of a suitable story. A few days later she eagerly eavesdropped on an exciting discussion between Byron and Percy about the nature of the principle of life and the possibility of artificially creating life, until she finally went to sleep in the small hours of the night. In bed, she lost herself in a dream. This was to become one of the most famous nightmares in the history of literature and must have occurred in the early hours of June 16, 1816. In the 1831 introduction, Mary described her nightly vision thus:

> "I saw – with shut eyes, but acute mental vision – I saw the pale student of unhallowed arts kneeling beside the thing he had put together. I saw the hideous phantasm of a man stretched out, and then, on the working of some powerful engine, show signs of life, and stir with an uneasy, half vital motion. Frightful must it be; for supremely frightful would be the effect of any human endeavour to mock the stupendous mechanism of the Creator of the world. His success would terrify the artist; he would run away from his odious handy-work, horror-stricken"
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> —Shelley, 2003 [1831]: 9.

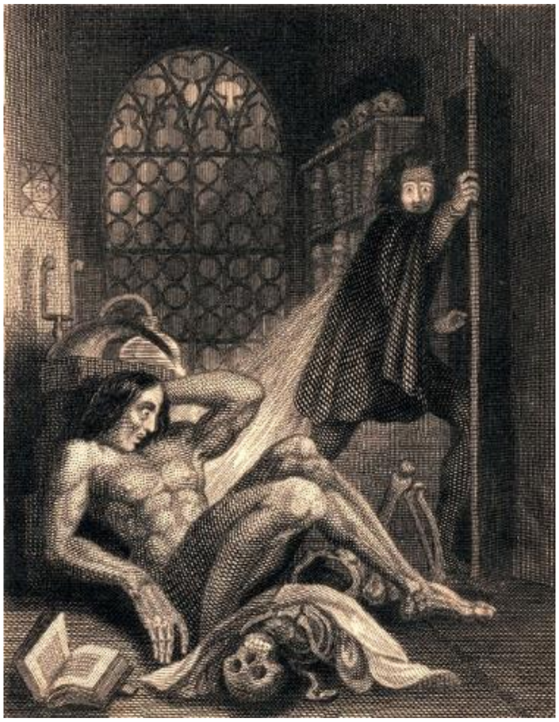

Figure 3. The 'Monster'; frontispiece of the revised 1831 edition of Frankenstein. Theodor von Holst (1831); image extracted and modified from Wikimedia Commons.

ELECTRICITY AND THE MYSTERY OF LIFE

So Mary finally had her ghost story. On Percy's instigation, she would elaborate and rework the story during the following months and years into a full-fledged novel. On the precise way the "thing" was brought to life, the book remains understandably somewhat vague. But there is a strong suggestion that electricity played an indispensable role in infusing the spark of life into the lifeless thing. In the 1831 introduction Mary referred to so-called 'galvanism', which enjoyed much interest at the time. At the beginning of the 19th century several sensational experiments had been made before public audiences with the newly developed Voltaic battery, showing that electric currents could be used to arouse muscular contractions and thereby to call forth motions of the body parts of dead animals or even human cadavers. It seemed as if those body parts could be "reanimated" in this way. In one notorious demonstration performed in 1803 before a London audience, Galvani's nephew Giovanni Aldini administered an electric current to the face of a freshly executed murderer, whereupon "the jaw of the deceased criminal began to quiver, and the adjoining muscles were horribly contorted, and one eye was actually opened" (London Morning Post, January 1803, quoted in Lederer, 2002: 14). It was not too far-fetched, therefore, to think that the mysterious principle of life had something to do with electricity. At any rate, electricity in the guise of lightning plays a major role in the depiction of the ambient atmosphere of the novel. Thus, after receiving the news about the death of his younger brother, Victor Frankenstein witnessed a "beautiful yet terrific" thunderstorm spectacle with dazzling flashes of lightning going to and fro above the Alps, the Jura and Lake Geneva (Shelley, 2003 [1831]: 77). The electrically charged atmosphere provided a fitting background to the vicissitudes in which Frankenstein and his creature got embroiled. Mary had derived this element of the novel from the exceptional weather conditions she actually experienced in Geneva. As she wrote in a letter to her half-sister in England: "The thunder storms that visit us are grander and more terrific than I have ever seen before" (Mary's letter to her half-sister Fanny Imlay, dated 1 June 1816; see Shelley, 1993 [1816]: 174).

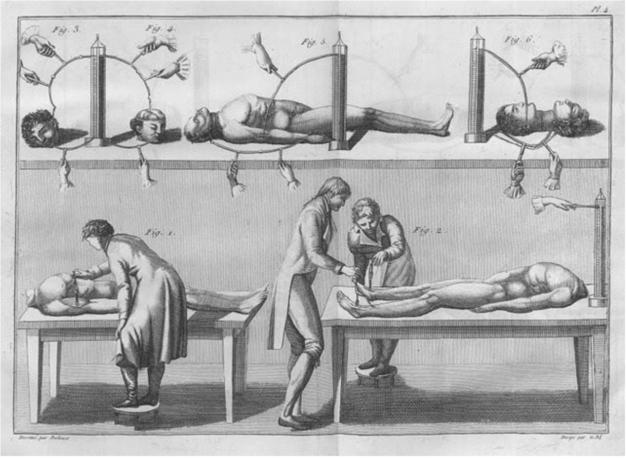

Figure 4. 'Galvanic' experiments on executed criminals performed by Dr. Giovanni Aldini (1804). Image extracted from Wikimedia Commons.

PROMETHEAN AMBITION

It is not difficult to associate electricity with fire through lightning and heavenly fire. In the title of her novel Mary alluded to the Greek myth about *Prometheus*, the Titan who had stolen fire from the gods to give it to humankind and who was severely punished for this act. Similarly, Victor Frankenstein brought disaster upon himself and his loved ones by indulging in the "unhallowed arts" of "bestowing animation upon lifeless matter" and by creating a human-like being. He aspired "to become greater than his nature [would] allow" (Shelley, 2003 [1831]: 54), or in other words, to play God. For Byron and Percy, however, Prometheus was also the iconic rebel hero who dared to defy the existing divine order in the name of promoting human happiness. In their eyes this endeavour should not even stop short of attempting to overcome death. Mary was apparently less enamoured by the Greek demigod celebrated by her romantic companions and was acutely aware of the possible downsides of "Promethean" ambitions. Or at least she was more ambivalent. As the biographer and historian Richard Holmes noted, the romantic generation of the Age of Wonder (1770–1830) had to discover both "the beauty and terror of science" (Holmes, 2009). Mary portrayed Victor Frankenstein as an investigator who is so much obsessed by his research project that he completely neglects his social obligations vis-à-vis his family, his friends and his fiancée. For her, the outstanding example of a passionately obsessed researcher was the English chemist Humphry Davy, whose main achievements were in the domain of electrochemistry (another connection with electricity and 'galvanism'!). In the first decade of the 19th century, Davy isolated new chemical elements like sodium and potassium with the help of the Voltaic battery. In his public lectures he also sketched an enticing prospect of the endless possibilities of chemical research that would bestow on man "powers which may be almost called creative" (Davy, 1802: 319). From reading these lectures Mary had concluded that scientists might at times be driven by a truly obsessive preoccupation. In this respect, Davy set the example for Victor Frankenstein: "So much has been done [...] – more, far more, will I achieve: treading in the steps already marked, I will pioneer a new way, explore unknown powers, and unfold to the world the deepest mysteries of creation" (Shelley, 2003 [1831]: 49) – this was how Victor Frankenstein described his new ambition after a university professor had pointed out the virtually unlimited possibilities of modern chemistry to him.

Figure 5. Humphry Davy isolated sodium and potassium by using the Voltaic battery. Magazine engraving (19th century), colored; image extracted from *fineartamerica*.

A FAILURE OF CARE AND RESPONSIBILITY

For some commentators, Frankenstein's moral transgression was not that he undertook the over-ambitious or hubristic attempt to bestow life on inanimate matter and thereby usurped the divine privilege. He must rather be blamed for the fact that, once his work finally met with success, he immediately ran away from "his odious handy-work". He thereby left his creature, which he himself had brought into the world, to its own fate – devoid of any parental care. The middle part of the novel, which follows the creature's life and vicissitudes, is a morality tale in its own right. From the outset, contrary to the portrayals in most movie versions, the creature is not a ruthless monster. It wants to do good and needs the company of fellow beings and their affection and recognition. However, the saying that when you do good, good things will happen to you did not apply to the creature. Due to its hideous appearance, it repeatedly met with rejection. Its attempt to remind Frankenstein of his parental duties was also to no avail. Only as a result of all these hostile responses did the creature become a monster, intent on revenging the injustices done to it with acts of violence. In an early review of the novel, Percy Shelley summarized the simple moral lesson thus: "Treat a person ill, and he will become wicked." (Percy Shelley, 1993: 186). Seen in this light, Frankenstein's greatest moral shortcoming was that he failed to assume responsibility for his own creature and to give it the care that it needed and deserved.

Figure 6. Another reading of the Frankenstein tale. Image extracted from Wikimedia Commons.

The American philosopher of technology Langdon Winner was the first to use this interpretation of the *Frankenstein* novel as a clue for dealing more responsibly with new technologies in general: "the issue truly at stake in the whole of *Frankenstein* [is] the plight of things that have been created but not in a context of sufficient care" (Winner, 1977: 313). His generalized ethical message is therefore that researchers who develop new technologies must be willing to assume responsibility for the vicissitudes of their creations, help them to acquire a suitable role in society and provide adequate follow-up care if necessary. Their task is by no means completed once a new technological prototype leaves the laboratory. With so much emphasis nowadays on the necessity of responsible research and innovation, Winner's message finds wide resonance. Similar interpretations of the Frankenstein tale have been propounded by Stephen Jay Gould (1996) and Bruno Latour (2012). Gould gives a pointed formulation of this new reading of Mary Shelley's novel:

> "Victor Frankenstein [...] is guilty of a great moral failing [...] but his crime is not technological transgression against a natural and divine order [...] Victor's sin does not lie in misuse of technology, or hubris in emulating God; we cannot find these themes in Mary Shelley's account. Victor failed because [...] he did not take the duty of any creator or parent: to teach his own charge and to educate others in acceptability."
> —Gould, 1996: 61.

Gould's flat denial that the themes of hubris in emulating God and transgression against a natural and divine order are nowhere to be found in Mary Shelley's account is quite astonishing. Traditionally, for many readers her novel is precisely *also* about these themes: they are by no means a later invention of Hollywood adaptations. Mary's introduction to the 1831 edition directly contradicts Gould's denial (see the passage quoted above). Thus the Dutch literary critic Pieter Steinz, for one, reaffirmed the traditional reading of *Frankenstein*: "The moral is clear, and it is more relevant than ever in the 21st century, which is dominated by the advancing genetic and bio-technologies: do not play God and beware of the dangers of technology" (Steinz 2002).

I therefore take it that the themes of hubris, transgression and playing God on the one hand and Victor's moral failure to take responsibility and proper care for his creature on the other are *both* contained in the novel, so that there is no need to embrace one element and completely dismiss the other. A nuanced and balanced view, in which the two strands of interpretation are indeed combined, can be found in Mary Threapleton's introduction to a 1963 pocket edition of *Frankenstein*:

> "In the course of the story, Frankenstein is horribly punished for [...] presuming to overstep man's proper bounds. His brother, his best friend, and his bride all fall victim to the monster he has created. *He is punished not only because he has dared to create it, but also because he fails to assume due responsibility for it.* He gave the monster life, but he was too horrified to guide it, to make it into a power for good."
>
> —Threapleton, 1963 (my italics).

THE NEW ORTHODOXY OF RESPONSIBLE INNOVATION

The Frankenstein Bicentennial Project, set up by researchers from Arizona State University, nevertheless promotes a reading of Mary Shelley's novel based one-sidedly on the interpretations of Winner, Gould, and Latour, while dismissing the traditional interpretation focusing on hubris and the dangers of playing God as singularly unhelpful. As some researchers affiliated with this project declare in a recent publication:

> "The moral of Frankenstein is not a warning about ungodly technoscientific creation; it is a warning against taking a position that does not consider matters of care and concern for those technoscientific creations. [...] Frankenstein's failure to care for his creation is his downfall – not his act of technological innovation. [...] The lack of care for new creations is what ultimately destroys us, not the creations themselves."
>
> —Halpern et al., 2016: 4, 6.

Although the authors admit that they read the *Frankenstein* novel "against the grain of many popular interpretations, which see it as a story about the abominations created when man decides to play God" (ibid., 4), they do not explain why they deem the common understanding incorrect as an interpretation of Mary Shelley's story. However, the protagonists of the Frankenstein Bicentennial Project may have good reasons for considering invocations of hubris and playing God "unhelpful tropes" for their own agenda of promoting responsible innovation, as these tropes tend to deny that "the human actors are responsible for their own decisions and for what they do with the fire of creativity" (ibid., 7). Indeed, one may readily admit that the standard objection of 'playing God', routinely raised against new developments in the modern life sciences, has been reduced to a facile journalistic cliché or an alarmist slogan, as I have argued myself in an earlier article (van den Belt, 2009). Still, this does not justify treating these themes as completely foreign to a proper understanding of Shelley's gothic novel, the more so, as the latter's use of the expression "unhallowed arts" clearly suggests that the very attempt to bestow life on lifeless matter may indeed be seen as "ungodly". The real interpretative challenge is to explain how the two different readings of the novel (hubris and playing God versus Frankenstein's moral failure to take care of his creature) can be reconciled, for there surely exists a tension between them.

If the goal is to promote responsible (research and) innovation – the underlying agenda of the Frankenstein Bicentennial Project – , it also will not do to declare public fears about hubris and playing God simply out of court. After all, an important part of the new agenda is to take public concerns about new technological developments seriously and to somehow address them in the further course of the innovation process. The general public may also be concerned, and rightly so, about the "Promethean" or "hubristic" projects often being contemplated by contemporary life scientists. However much people nowadays may admire their creativity and imagination, as Mary Shelley and her contemporaries did in an earlier age, they will also feel overwhelmed when the flights of the biotechnological imagination become a little too audacious. As Richard Holmes argues, it was Shelley's romantic generation which first had to face the beauty and terror of science (Holmes, 2009). It seems that we are still their cultural heirs.

Thus the emphatic assertion that "[t]he lack of care for new creations is what ultimately destroys us, not the creations themselves" is rather unfortunate in that it arbitrarily restricts the scope of meaningful social debate. It suggests that the public should refrain from discussing the desirability of the many new "creations" technoscientists are about to bring into the world and only see to it that proper care is offered afterward once they have been introduced. If we think about some of the wild ideas that currently circulate among synthetic biologists (*e.g.*, proposals to resurrect the woolly mammoth or Neanderthal man and schemes for "gene drives" or for changing the nucleotide 'letters' of the DNA alphabet), it immediately transpires that this is too narrow a view. Indeed, synthetic biologists and other life science researchers often set such bold targets that the audacity of the biotechnological imagination constitutes the contemporary equivalent of what was traditionally called hubris. Of course, their scientific and technological aims should not simply be rejected out of hand, but deserve to be seriously discussed – a discussion that might nonetheless be properly informed by cautionary tales about "Promethean" ambitions like Mary Shelley's *Frankenstein* story.

A final critical point about the interpretation endorsed by the Frankenstein Bicentennial Project is that their notion of responsibility vis-à-vis new technologies is largely modelled on the idea of care – the care Victor Frankenstein failed to bestow on his creature. Now we know fairly well what care means as long as we are talking about parental care towards children. So the creation of an artificial human being would presumably entail taking (parental) care for the new creature, however hideous it may look. But it is far less clear what the idea of care involves when we are talking about the creation of non-human life-forms; and even less so when talking about inanimate technologies. Bruno Latour's call to "care for our technologies as we do for our children" (Latour, 2012) is simply begging the question. In sum, a proposed ethics of care for responsible innovation sounds nice, but also remains somewhat vague.

Figure 7. The monster demands a mate! Poster for the movie Bride of Frankenstein (Universal Pictures, 1935). Image extracted from Wikimedia Commons.

VICTOR FRANKENSTEIN'S REFUSAL TO CREATE A FEMALE COMPANION

There is one episode in Mary Shelley's novel where Victor Frankenstein finally appears to become a responsible agent and to act responsibly, but this very episode is ignored and not discussed by the proponents of responsible innovation. I am alluding to the dramatic moment at a later stage in the novel when he is at first inclined to comply with his creature's wish to have a female companion created for it, but then has second thoughts and refuses the request. He had already been working on the creation of a female being, but then decided to destroy her in her unfinished state rather than complete the job. The considerations that led him to this decision look very much like what today would be called an invocation of the Precautionary Principle. The creature had suggested that it might leave Europe and go with its female mate to an uninhabited part of South America, but Frankenstein pondered the possible long-term consequences with much anguish:

> "Even if they were to leave Europe, and inhabit the deserts of the new world, yet one of the first results of these sympathies for which the demon thirsted would be children, and a race of devils would be propagated upon the earth, who might make the very existence of the species of man a condition precarious and full of terror."
> —Shelley, 2003 [1831]: 170–171.

Thus Frankenstein's refusal to create a female mate can be seen as an act of responsibility after all, based on precautionary motives. As Leonard Isaacs writes, "Like most tragic protagonists Frankenstein has learned from his experience. With a painfully acquired sense of the wider consequences of his actions, he takes on the heavy responsibility of opposing the development of second-generation monsters" (Isaacs, 1987: 71; Isaacs draws an interesting parallel between Frankenstein and J. Robert Oppenheimer, who after the development of the atomic bomb was under pressure to develop a 'second-generation' nuclear bomb). The possibility of uncontrolled reproduction is a biological hazard that also has to be taken into account when we create transgenic and synthetic organisms today. Later on Frankenstein justified his decision on the basis of a kind of utilitarian reasoning in terms of the greatest happiness for the greatest number:

> "In a fit of enthusiastic madness I created a rational creature, and was bound towards him, to assure, as far as was in my power, his happiness and wellbeing. That was my duty; but there was another still paramount to that. My duties towards the beings of my own species had greater claims to my attention, because they included a greater proportion of happiness or misery. Urged by this view, I refused, and I did right in refusing, to create a companion for the first creature."
> —Shelley, 2003 [1831]: 219–220.

Incidentally, this whole reasoning is of course predicated on the assumption that the artificial creature was *not* a member of the human species. From the very outset, its taxonomic status had been somewhat ambiguous. While Frankenstein's intention had indeed been to create an artificial human being (Shelley, 2003 [1831]: 54), his initial speculations were also focused on creating a new species: "A new species would bless me as its creator and source; many happy and excellent natures would owe their being to me. No father could claim the gratitude of his child so completely as I should deserve theirs" (ibid., 55). It is safe to conclude that the human status of the artificial creature has been problematic from the start.

From the viewpoint of an ethics of care one could argue that Frankenstein should have complied with the creature's demand to have a female companion created for it, given his parental duty to assure its happiness and wellbeing and given that the creature after many attempts had failed to acquire a recognized place in human society. On the other hand, it cannot be denied that there is also ethical merit in Frankenstein's decision to decline the creature's wish. At the very least, then, the whole episode could be an interesting test case for probing our moral intuitions about what would be truly responsible action in the given situation.

Two researchers recently formalized Victor Frankenstein's reasoning by setting up mathematical models of species interaction, in particular modelling situations of "competitive exclusion" between two species. They conclude that "[Frankenstein's] rationale for denying a mate to his male creation has empirical justification" and that "the central horror and genius of Mary Shelley's novel lie in its early mastery of foundational concepts of ecology and evolution" (Dominy & Yeakel, 2016). This is a rather surprising new reading of the novel.

We may finally wonder why the proponents of responsible innovation have passed in silence over the entire episode of the novel. Perhaps it is because a (presumably) responsible decision not to create a new entity would not fit their presumption that is not the "new creations themselves", but only our own lack of care for them that can bring us down.

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Journal of Geek Studies
ISSN 2359-3024

Fantastic beasts and how to diversify them

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Despite their secrecy, fantastic beasts are oftentimes noticed by muggles. Their diversity, however, was never subject of any study in order to understand what could have driven it. At least two groups of creatures show that both historical and environmental aspects played role on these organisms' lineages' splitting events, leading to their current distribution on the globe. Additionally, nonspecialist readers that enjoy *Harry Potter* culture might become interested in the topic and, as such, fictional content can represent an innovative tool of science outreach to introduce evolutionary biology and biogeography concepts to the general public.

WHERE AND WHO ARE THEY?

Not even special clauses (Scamander, 2001) prevented muggles of noticing fantastic beasts among them. They are part of our days probably since before we started creating tales about them (d'Huy, 2013). Present in all continents, except Antarctica, magical creatures occupy an unequal variety of niches, from herbivorous forms to fire-eating beasts (Scamander, 2001). All the main differences described for such creatures may reflect not just local traditions or modifications from oral stories, but actual lineage branching events (*e.g.*, Hamilton et al., 2015).

Among such beasts, there are some groups in which well-known diversification processes can be exemplified, namely a clade of hominoid-related beasts, and a clade of insect-related creatures, both currently spread in the European and North American continents (Fig. 1; topology follows Gerelle et al., 2016). Basically, the appearance of natural barriers, as well as opportunistic exploitation of diverse ecological niches, could be the main causes explaining where such fantastic creatures currently inhabit (*i.e.*, their geographic distribution); this would be in spite of the common explanation of climate change driving biodiversity dynamics (*e.g.*, Janis, 1993; Alroy et al., 2000).

INSECT-RELATED HUMANOID BEASTS

According to Gerelle et al. (2016), Fairies, Imps, Pixies, Grindylows, and Doxies form the sister clade to butterflies (crown-Lepidoptera), making them a sort of 'lepidopteran-like' beasts. Despite being phylogenetically related to insects, all creatures in this clade possess humanoid traits, consisting of a remarkable case of evolutionary convergence. In addition, the absence of wings in Grindylows and Imps is probably a case of reversion to the apterous plesiomorphic condition of insects (*i.e.*, the insect lineage was originally wingless; Kukalová-Peck, 1991).

Figure 1. Current distribution of the groups discussed in the text with their phylogenetic relationships, based on Gerelle et al. (2016).

It is plausible to assume that the split between crown lepidopterans and lepidopteran-like fantastic beasts occurred back in the earliest Jurassic (Hettangian) of Britain (circa 200 Ma, *i.e.*, 200 million years ago), as this is where the oldest fossil lepidopteran comes from (Whalley, 1986; Schachat & Gibbs, 2016). At that time, continents were united in a single land mass, called Pangaea, which would have allowed some populations of 'Doxy-like' beasts to migrate from British areas to what is now North America (Fig. 2A). This would explain why Doxies are present in both continents, but the remaining representatives of the group are not, demonstrating another case of disjunct distribution, as occurs, for example, with ratite birds, some pleurodiran turtles and flowering plants (Wen, 1999; de Queiroz, 2005). Otherwise, Doxies might have later migrated to North America through land continuities such as the De Geer Bridge (McKenna, 1975).

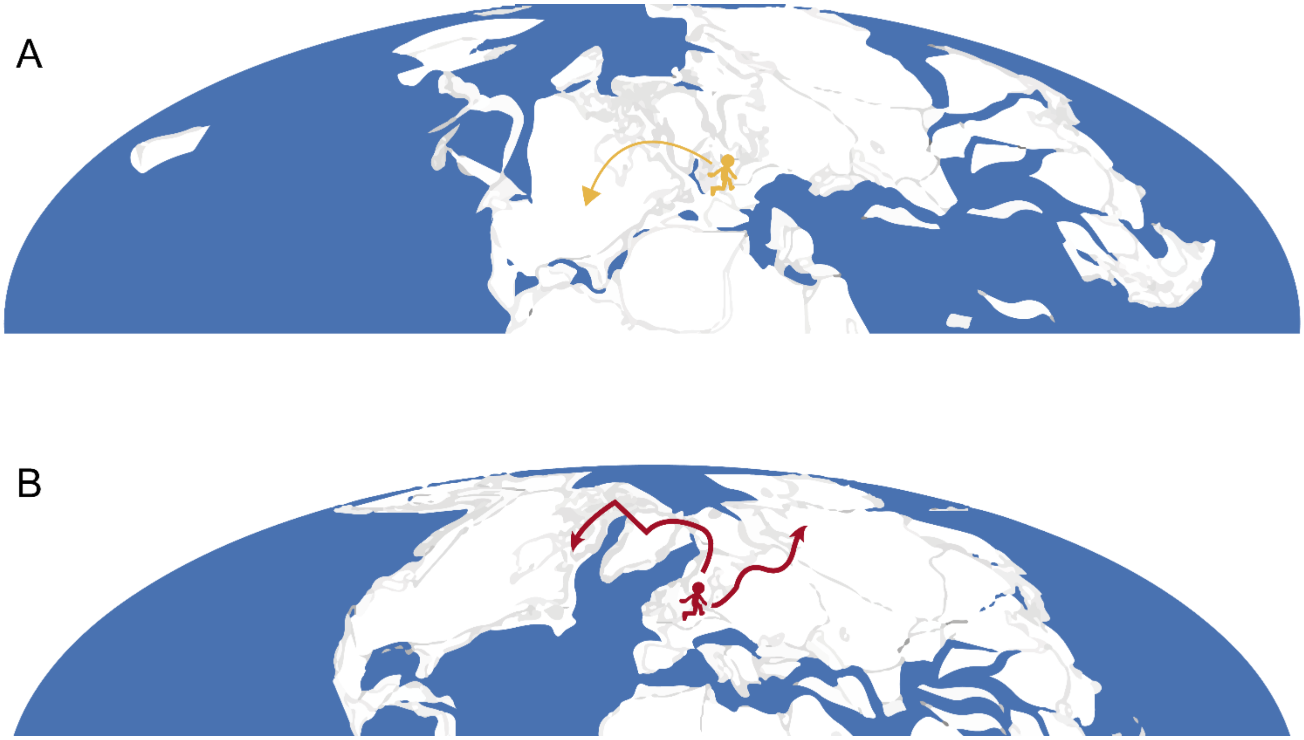

Figure 2. Probable location of ancestors of **(A)** the lepidopteran-like beasts during the Hettangian (earliest Jurassic) of Britain, with posterior migration to North America, and **(B)** hominoid-related beasts, originating in Central Europe during the Paleogene, with subsequent migration to northern Europe and North America. Maps modified from the Paleobiology Database (PBDB; www.paleobiodb.org).

Grindylows branched early in this clade's evolutionary history, "soon" after the Doxy lineage separated, likely dating to the Toarcian (late Early Jurassic; circa 180 to 175 Ma), when England was flooded by marine transgressions (Wignall, 1991). The populations occupying the deluged area probably vanished, while the ones remaining at its borders survived and later invaded the aquatic environment (organisms closely related to modern Grindylows). This is somewhat akin to the Pleistocene refuge hypothesis of Neotropical diversification (*e.g.*, Vanzolini & Williams, 1981; Garzón-Orduña et al., 2014), but instead of forest retraction due to climate fluctuation, areas underwent fragmentation because of marine water incursion.

Like the other splitting events, Imps and Pixies diverged mainly due to historical causes. Both beasts share morphological and reproductive similarities (Scamander, 2001). Pixies are restricted to Cornwall, whereas Imps are distributed throughout Britain, living near river banks. In Cornwall, the River Tamar largely represents the boundary with the rest of England (Carey, 1911). The rise of sea-level (similar to that of the last interglacial period; Rohling et al., 2008), could have flooded the river region, isolating populations that lived near it (like modern Imps do). On the Cornish side of the river, a small population would have differentiated, preventing gene flow after the restoration of sea levels (Fig. 3). Despite capable of flying (and thus crossing the river), Pixies are not known to form hybrids with Imps.

According to folklore, Fairies are exclusively British creatures (Briggs, 1967; Silver, 1999), but the lack of information regarding ecological preferences (Scamander, 2001), as well as fossils, hinder speculation about their evolutionary history.

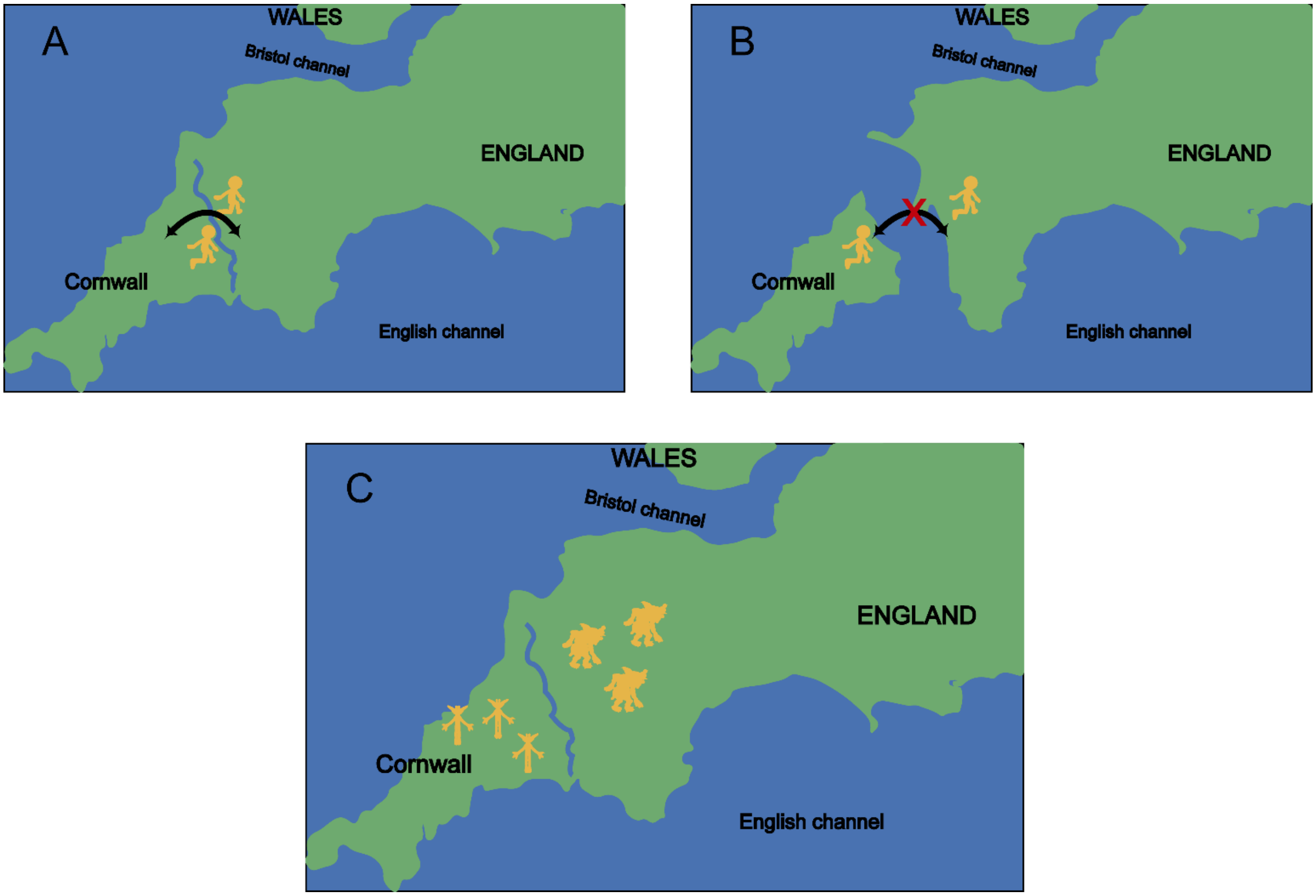

Figure 3. (A) Geographical distribution of 'Pixie + Imp' ancestor in southwestern England. **(B)** Vicariant event isolating two populations and preventing gene flow. **(C)** Current distribution of Imps and Pixies, the latter being restricted to Cornwall.

HOMINOID-RELATED BEASTS

It is likely that, instead of historical events causing populations to split, ecological constraints were mainly responsible for the current diversity of hominoid-related beasts. The first branching lineage to be analyzed is the clade formed by Gnomes, Red Caps, and Leprechauns. As hominoid-related beasts, the group probably originated at least before the Miocene (a period spanning roughly 23 to 5 Ma; Stevens et al., 2013) and later invaded European landmasses. The burrowing habit of Gnomes most likely resulted of selective pressure due to the predation by Jarveys, a large ferret-like beast present both in Europe and North America. As such, the plesiomorphic (*i.e.*, ancestral) condition of the group was a non-burrowing habit, which might have evolved independently in Red Caps too (Scamander, 2001). The occurrence of Gnomes in both

Europe and North America depicts again a case of disjunct distribution, but the processes that drove such pattern probably differ from that of the Doxy. Rather than a vicariant event resulting from the split of Laurasia, climatological events could have created a passage that allowed them to reach North America (*e.g.*, the Thulean Bridge; Brikiatis, 2014), as exemplified by marine diatoms during the Eocene (Bijl et al., 2013). As Jarveys intensively preyed on Gnomes, some populations likely sheltered in tunnels and acted as scavengers, feeding on the blood shed by their kin (similar to modern Red Caps).

In turn, Leprechauns likely represent a more recent lineage that migrated to Britain at first (still connected to the European mainland; Erlingsson, 2004) and then reached Ireland, probably across a land bridge before humans (Edwards & Brooks, 2008; Bower, 2016), being later included in Irish folklore (Winberry, 1976; Koch, 2006). However, Leprechauns (as all the exemplified beasts) lack a fossil record, which complicates the understanding of how and when such groups colonized the areas they currently live in (Crottini et al., 2012).

The other clade of hominoid-related beasts comprises Erklings, Trolls and Progebins, distributed in northern Europe (Fig. 4A). Modern representatives of the group are known to feed on flesh (especially human; Scamander, 2001), which evokes whether such beasts arose earlier or later than the *Homo* arrival to Europe (ca. 1.4–1.8 Ma; Parfitt et al., 2005; Toro-Moyano et al., 2013). Probably spread all over Europe originally, the competition for the same kind of resources (mostly raw flesh) with a distantly related clade

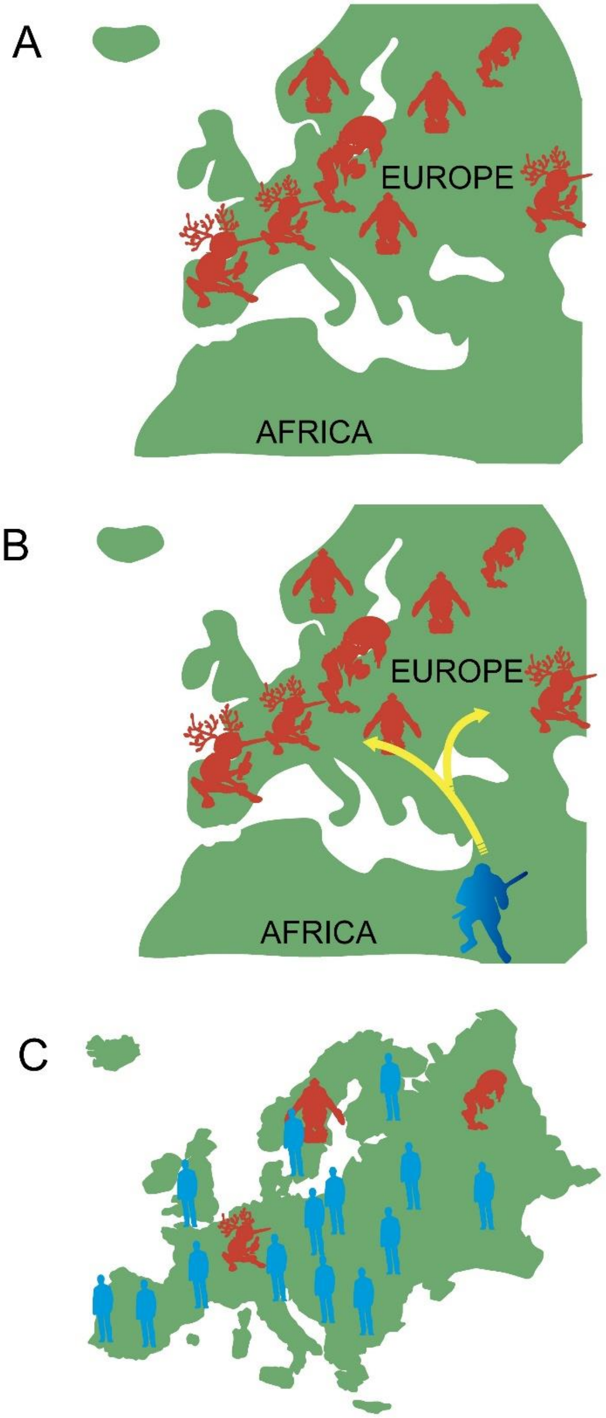

Figure 4. (A) Probable ancient distribution of Erklings, Trolls, and Pogrebins in Europe. **(B)** Arrival of *Homo* species in Europe, ca. 1.5 Ma. **(C)** Demise of original populations of fantastic creatures, showing their current relictual distribution in Europe.

(*Homo* species) may have constrained the range of the group (mainly inhabiting densely vegetated zones today), extinguishing ancient populations more widely distributed. This last example analogously illustrates a case (*e.g.*, Silvestro et al., 2015) in which the later arrival of a phylogenetically distant (but ecologically similar) clade to an area triggered diversification shifts onto the previous occupiers, as well as the probable extinction of some forms.

BIOGEOGRAPHICAL HISTORY OF FANTASTIC BEASTS

In order to verify if there is a regionalization among the fantastic biota, their geographical distribution was compiled from Scamander (2001) and interpreted based on (i) six distinct geographical realms from Wallace (1876), and (ii) the recent division of Holt et al. (2013) in 13 domains. Each creature was plotted against the realm in a simple area vs. taxa matrix (*e.g.*, Souza, 2005), scoring (0) if absent, and (1) if present in a determined locality. This gives us a diagram, called 'area cladogram', with the biogeographic history of the groups.

The area cladogram obtained with Wallace's six biogeographic domains (Wallace, 1876) is partially consistent with the biogeographical history of the southern hemisphere (*i.e.*, mostly Gondwanan-derived land masses), according to patterns observed in some plants and animals (*e.g.*, Sanmartín & Ronquist, 2004), in which the Oriental biota (*i.e.*, mainly Indian) is the sister group to the remaining areas (Fig. 5A). This could be reasonably expected, since India was the first land mass to branch in Gondwana breakup geological sequence (Barron, 1987; McLoughlin, 2001). The relationships of African, South American and Australian areas however disagree with Sanmartín & Ronquist (2004), in which it was expected that South American and Australian biotas were more closely related to one another than to the African biota. This result could imply a Pangaean origin for these fantastic beasts, with subsequent vicariant events. However, this hierarchical pattern following the breakup sequence of Gondwana could also be a kind of 'vicariance-mimicking' phenomenon affecting the cladogram area topology (see Upchurch et al., 2002). Until fossils of fantastic beasts are found, knowledge about their past distribution remains obscured. On the other hand, when plotted according to the biogeographic realms of Holt et al. (2013) the Gondwanan-derived continents do not present such hierarchical relationship (Fig. 5B), resulting in a pectinate (*i.e.*, comb-like) conformation within the area cladogram. Both results could also be influenced by the lack of data about the fantastic beasts, which may not follow the pattern of ordinary ones.

In sum, due to the incompatible results for Gondwanan continents, the fantastic biota could have had a hybrid, composed origin (Amorim, 2012), with both autochthonous and allochthonous elements. The Palearctic and Nearctic realms were recovered together in both analyses, although both regions are inhabited by most of the beasts, which could have biased the result. Despite of the apparently unarguable Laurasian distribution of such beasts, it has been historically difficult to depict the continents' biogeographical scenario (Sanmartín et al., 2001; Wildman et al., 2007).

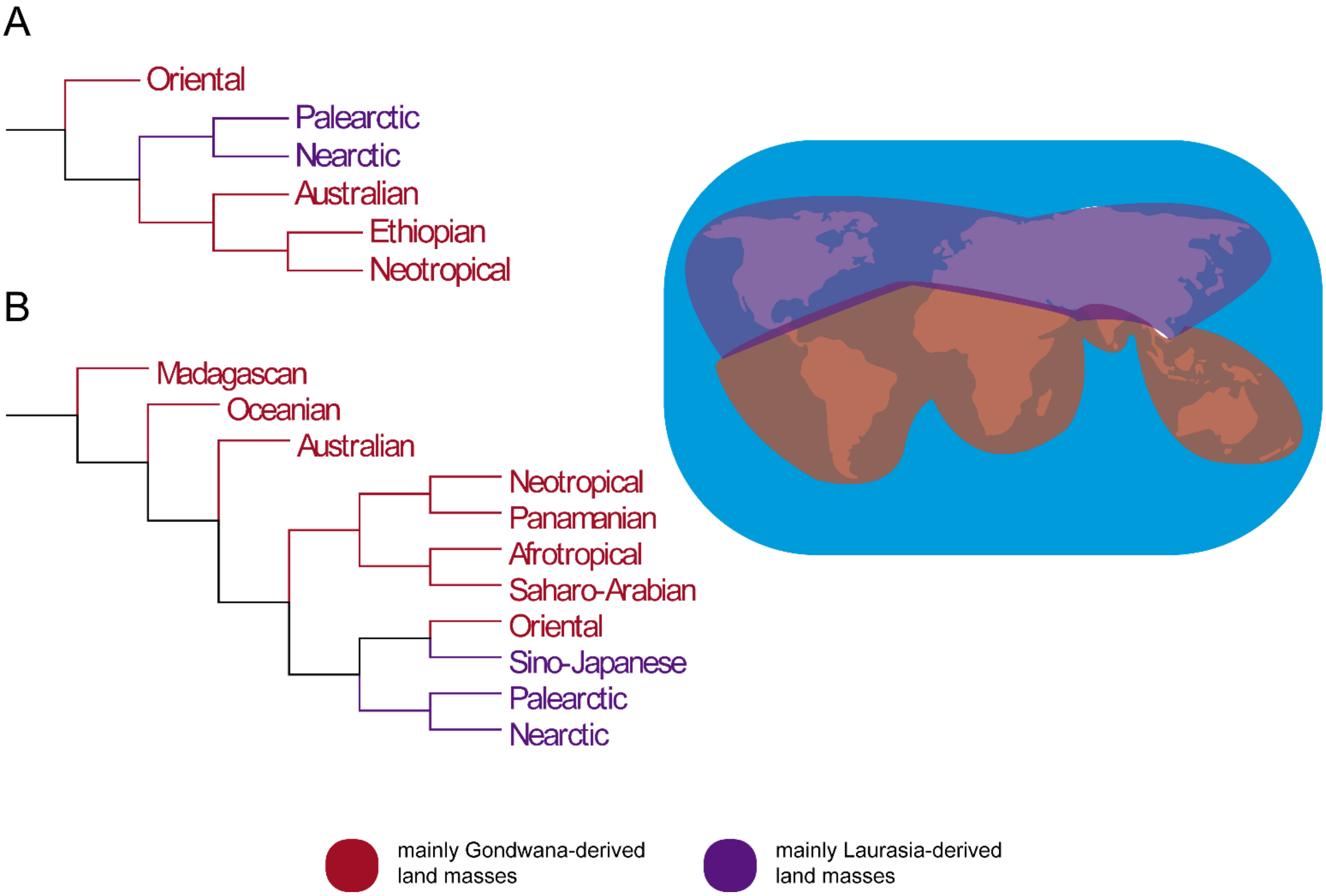

Figure 5. Area cladograms obtained based on **(A)** Wallace's zones (1876), and **(B)** Holt et al. (2013) new zones, subdividing those proposed by Wallace.

FICTION AS SCIENCE OUTREACH

Biogeography is an integrative science combining different sources of evidence to understand what caused organisms to be distributed the way they presently are – or were in the geological past (Lomolino et al., 2010). Despite of its relevance, the public knowledge (*i.e.*, outside the academic environment) concerning this research area seems debilitated, even with the timid increase in electronic dissemination (Ladle, 2008). Present in both evolutionary approaches of Darwin (1859) and Wallace (1876), the spatial distribution of organisms offers an unparalleled tool to stimulate students to think about evolution and natural history (Rosenau, 2012; Allchin, 2014) – and not just to understand evolution, but to accept it as well (Lombrozo et al., 2008).

In this context, the teaching of biogeography (and evolution in general) could benefit from the use of fictional organisms with "real" distributions around the globe. Presenting the continents' past and present arrangement, allied with the localities inhabited by the beasts and possible disjunction events, in a kind of inquiry-based approach (*e.g.*, Robbins & Roy, 2007) would instigate students to formulate their own hypotheses. This, in turn, could lead them to more easily assimilate all these concepts. The specific use of the popular *Fantastic Beasts* of the *Harry Potter* franchise to canalize this is supoprted mostly by the interest of younger audiences (under 25 years old) in the recently released spin-off movie (over 50%; Lang, 2016). Actually, scientific scenarios were already present on several episodes from the *Harry Potter* books (*e.g.*, Rowling, 1997; 1998; 1999; 2005), providing a larger background for people to get involved.

Moreover, this would not be the first time that a fictional universe was considered to engage younger people on scientific activities (*e.g.*, Roque, 2016). J.K. Rownling's fantasy novels are already proven as a promising and innovative background for scientific experiments (*e.g.*, Vezzali et al., 2014). As such, the present work is hopefully in a good position to arouse at least a spark of interest among students to understand what made our beasts – fantastic or otherwise – to live where they do.

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ACKNOWLEDGMENTS

I would like to thank J.K. Rowling, who idealized the magical world of *Harry Potter* as well as its fantastic creatures; my Biogeography professor, Eduardo Almeida, in whose course I was able to formulate ideas regarding the subject; my colleagues (Anaís Silveira, Carolina Barroso, Fernanda Dalarmi, Isabela Soares, Luene Pessoa e Thayná Medeiros) with whom I worked in said course, as well as Nádia Gibran, for all the support and kindness. The author is funded by the *Fundação de Amparo à Pesquisa do Estado de São Paulo* (FAPESP; proc. 2016/03373-0).

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Journal of Geek Studies

ISSN 2359-3024

Who is that Neural Network?

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Pokémon has been an enormous success around the globe for more than 20 years. In this paper, I tackle the "Who's that Pokémon?" challenge from a machine learning perspective. I propose a machine learning pre-processing and classification pipeline, using convolutional neural networks for classification of Pokémon sprites.

COMPUTING AND IMAGE RECOGNITION

Since they were invented[1], computers became increasingly present in our everyday life. Initially restricted to mathematical problem-solving and military applications in ballistics and cryptography, their applications become more diverse by the minute. As of today, machines beat humans in lots of tasks, one of the most recent being AlphaGo's victory over the Go world champion (Go Game Guru, 2017).

This achievement is a testament to the remarkable advances sustained by machines towards intelligent applications. Go, with its almost infinite combinations[2], is not an easy problem to solve by "brute force"[3], the strategy usually employed by computers against humans in other perfect information games.

But do not despair, for not all is lost in our fight against our future robot overlords, as computers still struggle with a task that humans were quite literally born to do: image and pattern recognition. However good a computer may be today, humans are still way better at noticing that, even though Figure 1 shows a car, something quite unusual happened to it.

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[1] The exact date for the invention of the computer is quite difficult to pin down. Helpful devices for calculations have existed for centuries, but truly programmable computers are a recent invention. If we take as a cutoff criterion that the first computer must be Turing Complete (that is, being able to compute every Turing computable function), our first examples would be placed around the first half of the twentieth century. The first project of a Turing complete machine is attributed to Charles Babbage in the nineteenth century. His Analytical Engine, if ever built, would be a mechanical monstrosity of steel and steam that, although not very practical, would certainly be awesome.

[2] It is estimated that the game space of Go comprises around $2.08 \cdot 10^{170}$ legal positions or 208,168,199,381, 979,984,699,478,633,344,862,770,286,522,453,884,530, 548,425,639,456,820,927,419,612,738,015,378,525,648, 451,698,519,643,907,259,916,015,628,128,546,089,888, 314,427,129,715,319,317,557,736,620,397,247,064,840, 935, if you want to be precise (Tromp & Farnebäck, 2016).

[3] Brute force search is a problem-solving strategy that consists in enumerating all possible solutions and checking which solves the problem. For example, one may try to solve the problem of choosing the next move in a tic-tac-toe game by calculating all possible outcomes, then choosing the move that maximizes the chance of winning.

Figure 1. Crashed car against a tree. This text was definitely not written by a robot overlord (yet). (Image extracted from Wikimedia Commons; Thue, 2005).

But computers are catching on! Advances in machine learning techniques, especially in supervised learning methods, and the ever-growing data available for feeding these algorithms have been enabling giant leaps in this field. In 2015, a 150 layers' residual neural network ensemble, trained by the MSRA team, achieved a 62% average precision in the 2015 image classification challenge with a data set with more than 1,000 different objects (Large Scale Visual Recognition Challenge, 2015).

Figure 2. Some simple things may be hard to a computer. ("Tasks"; XKCD, available from https://xkcd.com/1425).

So, we wonder... How would our machines fare against a challenge tackled by children around the world for the last 22 years?

Figure 3. Who's that Pokémon? (Screenshot from the Pokémon animated series.)

POKÉMON

Pokémon is an extremely successful franchise of games and animated series targeted at young audiences (although some people, as the author, disagree with this classification). The franchise was created by Satoshi Tajiri in 1995, with the publishing of two games for Nintendo's handheld console *Game Boy*. In the game, the player assumes the role of a Pokémon trainer, capturing and battling the titular creatures. It was an enormous success, quickly becoming a worldwide phenomenon (Wikipedia, 2017b).

The franchise started with a total of 151 monsters (Fig. 4), but today the games have reached their seventh iteration, counting with a total of 802 monsters.

Figure 4. Left to right: Bulbasaur, Charmander and Squirtle. (Official art by Ken Sugimori; image taken from Bulbapedia, 2017).

Each Pokémon belongs to one or two types indicating its "elemental affinity", as well as its strengths and weakness against other types. This feature is essential to the gameplay, establishing a deep and complex rock-paper-scissor mechanic that lays at the foundation of the combat system. There are 18 types (they were only 15 in the first game), as seen in Figure 5 (Bulbapedia, 2017).

Normal	Fighting	Flying	Poison	Ground	Rock	Bug	Ghost	Steel
Fire	Water	Grass	Electric	Psychic	Ice	Dragon	Dark	Fairy

Figure 5. The 18 Pokémon types, depicted with their usual background colors.

In this paper, I examine the performance of convolutional neural networks (also known as ConvNets) in a Pokémon Type classification task given a Pokémon game sprite. I will present the data collected, the pre-processing and training pipelines, ending with the performance metrics of the selected model. All the data, implementation code and results, as well as a Jupyter Notebook with the explanation of all the steps, are available in a GitHub repository (https://github.com/hemagso/Neuralmon).

DATA PREPARATION

Dataset Features

To train the models, I am going to use game sprites. The dataset (the sprite packs) was obtained at Veekun (2017). These packs contain sprites ripped from the games' so-called generations 1 to 5. Although there have been new games (and new monsters) released since then, they use tridimensional animated models; making it harder to extract the resources from the games, as well as making it available in a format that can be fed to a machine learning method. As such, in this paper we will only use Pokémon up until the fifth generation of the games (649 in total).

Figure 6 depicts the sprites of the three first-generation starters throughout all the games considered in this study.

We can immediately see that detail level varies between games, due to the different hardware and capabilities of the gaming consoles. The first generation, released for Nintendo's *Game Boy*, has almost no hue variation in a single sprite, although there is some hue information in the dataset (for instance, Bulbasaur is green, Charmander is red and Squirtle is blue; Fig. 6). As we go on, through *Game Boy Advance* to *Nintendo DS*, we see that the level of detail skyrockets, not only in terms of hue, but also in shapes.

At a first glance, we can also identify some typical problems encountered in image classification tasks. The images have different sizes. Even though the Aspect Ratio in all images stays at a one-to-one ratio, we have images ranging from 40-pixel width in the first generation to 96-pixel width in the fifth one (pay attention to the scales on the border on each sprite in Figure 6).

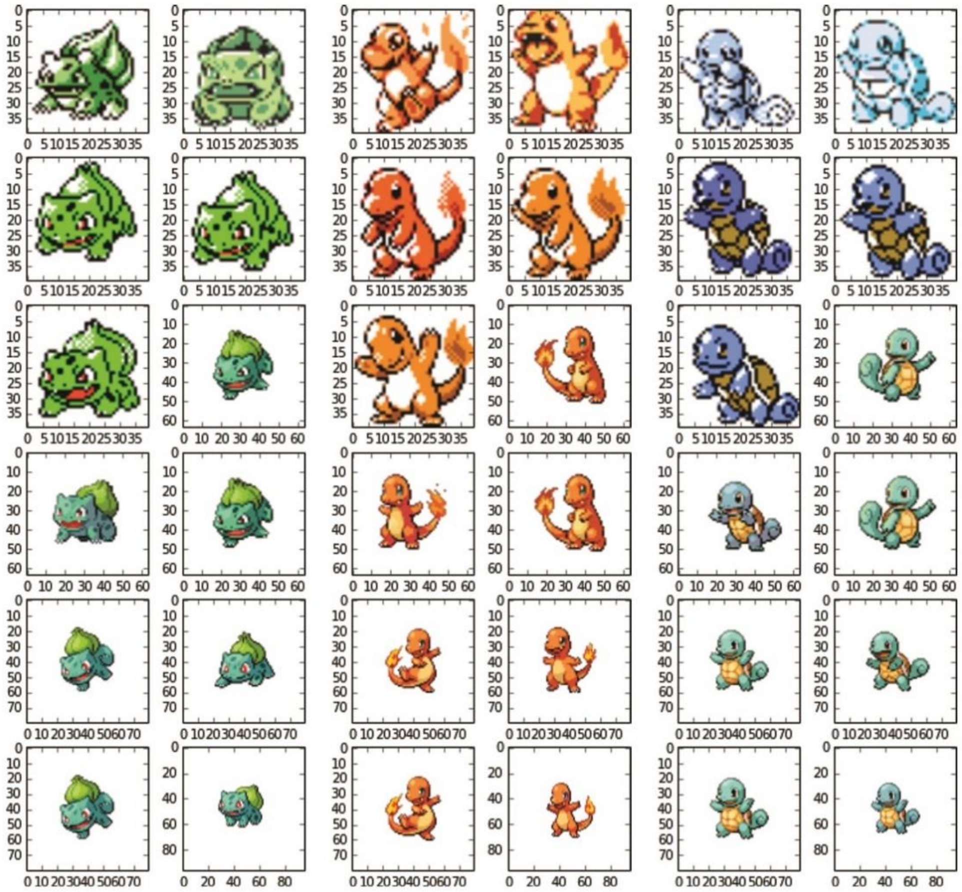


Figure 6. Example of the variation of the sprites for three Pokémon, as seen throughout games and generations.

Also, not all sprites fill the same space in each image. Sprites from the oldest generations seem to fill, in relative terms, a bigger portion of their images. This also happens within the same generation, especially in newer games, relating, in general, to the differences in size of each Pokémon and its evolutions (Fig. 7).

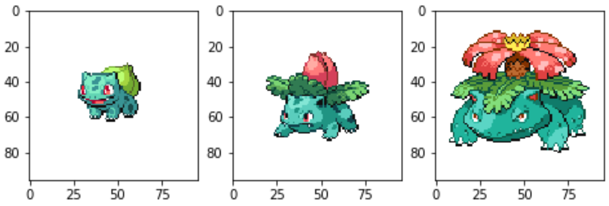


Figure 7. Bulbasaur's evolutionary line, as seen in the game's 5th generation. As the Pokémon evolves and gets larger, its sprite fills up a larger portion of the image.

Image Centering

To solve this problem, let's apply some computer vision techniques to identify the main object in the image, delimitate its bounding box and center our image on that box. The pipeline for that is:

1. Convert the image to grayscale.
2. Apply a Sobel Filter on the image, highlighting the edges of the sprite. The Sobel filter is a 3x3 convolutional kernel (more about these handy little fellows later, but see also Sckikit-Image, 2017) that seeks to approximate the gradient of an image. For a given image 'A', the Sobel operator is defined as:

$$G_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} * A \quad G_y = \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} * A$$

3. Fill the holes in the image, obtaining the Pokémon's silhouette.

4. Calculate the Convex Hull of the silhouette, that is, the smallest convex polygon that includes all pixels from the silhouette.

5. Define the square bounding box from the convex hull calculated before.

6. Select the content inside the bounding box, and resize it to 64 x 64 pixels.

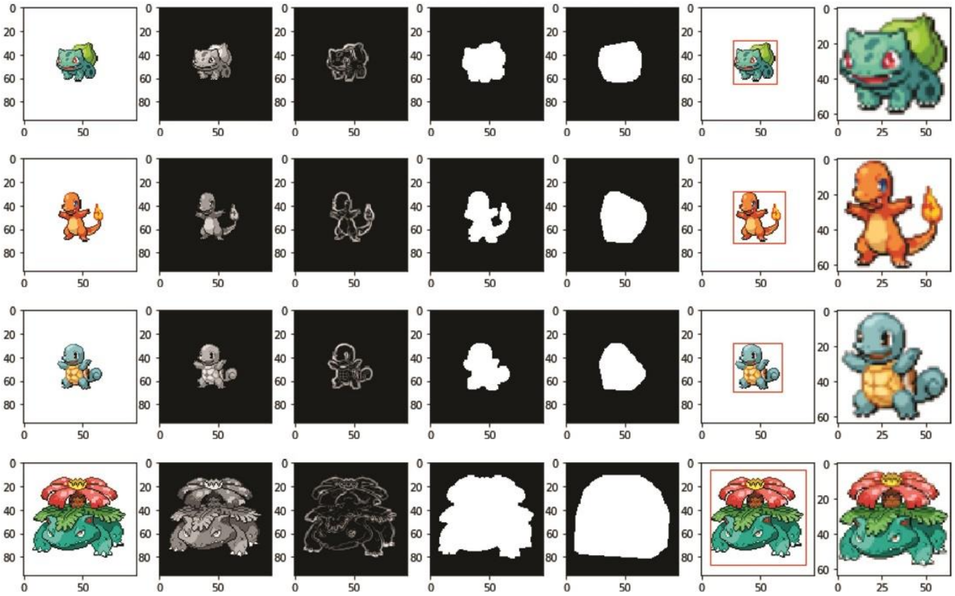


Figure 8. Examples of all steps of the sprite centering pipeline.

After following the pipeline outlined above, we obtain new sprites that maximize the filling ratio of the sprite on the image. Those steps were taken using *skimage*, an image processing library for the *Python* programming language. Figure 8 shows the results of our pipeline for the sprites of the three 1st generation starters and Venusaur.

Our proposed pipeline is extremely effective at the task at hand. That is to be expected, as our images are very simple sprites, with a very clear white background.

Finally, let's apply our method on all our monsters and images. Figure 9 shows the results for a bunch of Pokémon.

Figure 9. Centering results over various 5th gen Pokémon.

Target Variable

Now that we have all our Pokémon images to build our image dataset, we have to classify them in accordance with the variable that we want to predict. In this paper, we will try to classify each Pokémon according to its correct type using only its image. For example, in Figure 10 we try to use the image inside the bounding box to classify the Pokémon in one of the 18 types, trying to match its true type (shown below each Pokémon).

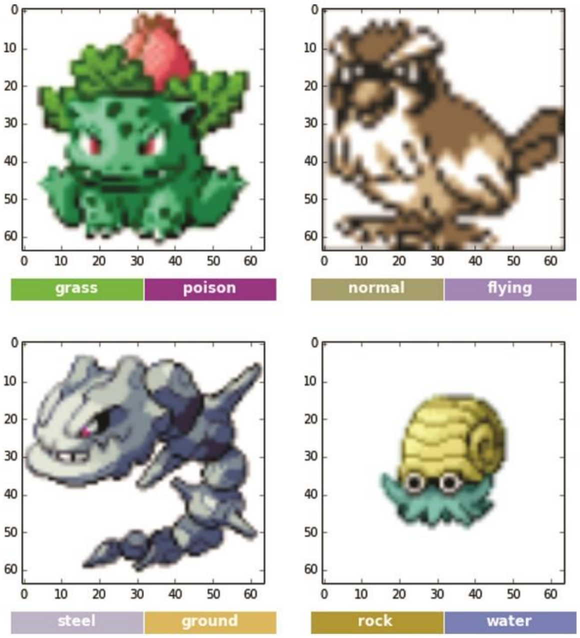


Figure 10. Example Pokémon and their respective types. Top row: Ivysaur (left) and Pidgey (right). Bottom row: Steelix (left) and Lord Helix (right), praise be unto him.

But there is a catch. A significant portion of the Pokémon, like all those from Figures 9 and 10, have a dual type. That is, its true type will be a combination of two different types from that list of 18 types. In Figure 10, for instance, Ivysaur is both a Grass type and Poison type, and has the strengths and weakness of both types.

To take this into account, we would have to make our target classifications over the combination of types. Even if we disregard type order (that is, consider that a [Fire Rock] type is the same class as a [Rock Fire] one), we would end up with 171 possible classes. (Actually, this number is a little bit smaller, 154, as not all combinations exist in the games.)

To make things worse, some combinations are rare (Fig. 11), with only one or two Pokémon, thus limiting the available samples to learn from.

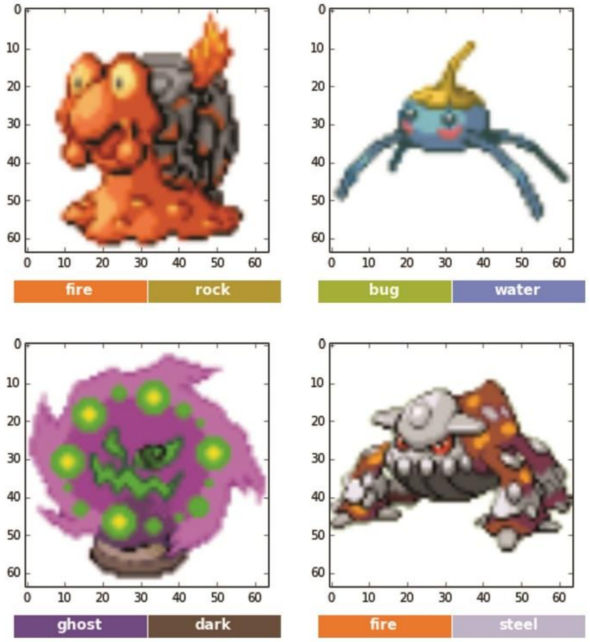


Figure 11. Some unique type combinations. Top row: Magcargo (left) and Surskit (right). Bottom row: Spiritomb (left) and Heatran (right).

Due to the reasons outlined above, I opted to disregard type combinations in this paper. As such, we are only taking into account the primary type of a Pokémon. For instance, in Figure 10 we would have: Ivyssaur: Grass; Pidgey: Normal; Steelix: Steel; Lord Helix: Rock.

MODEL TRAINING

Chosen Model

I used a convolutional Neural Network as a predictor on our dataset. Neural networks are one among many kinds of predictive models usually used in machine learning, consisting of an interconnected network of simple units, known as Neurons. Based on a loose analogy with the inner workings of biological systems, Neural Networks are capable of learning complex functions and patterns through the combination of those simple units (Wikipedia, 2017a).

In its simplest form, a Neuron is nothing more than a linear function of its inputs, followed by a non-linear activation function (Fig. 12). However, through the combination of several layers, neural networks are capable of modelling increasingly complex relationships between the independent and dependent variables at hand (Fig. 13).

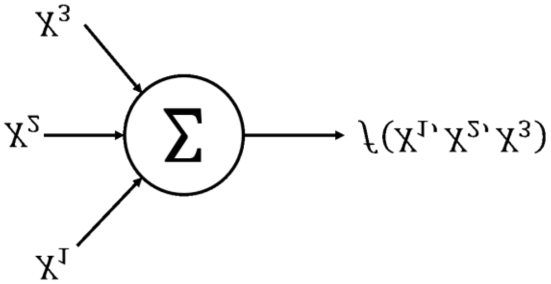


Figure 12. The basic unit of a Neural Network.

Neural networks are not exactly new, as research exists since 1940 (Wikipedia, 2017a). However, only with recent computational advances, as well as the development of the backpropagation algorithm for its training, that its use became more widespread.

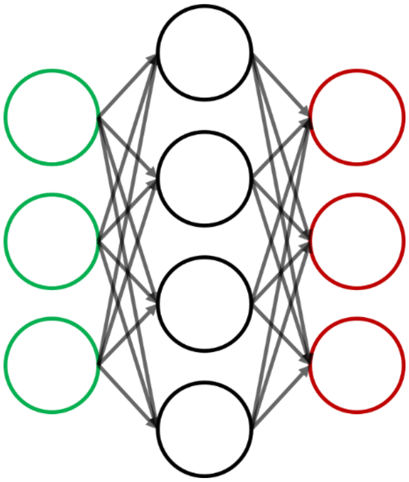


Figure 13. A slightly more complex architecture for a neural network, with one hidden layer.

OK, this is enough to get us through the Neural Network bit. But what the hell "convolutional" means? Let's first talk a little about Kernels.

In image processing, a Kernel (also known as Convolution Matrix or Mask) is a small matrix used in tasks as blurring, sharpening, edge detection, among others. The effect is obtained through the calculation of the matrix convolution against the appropriate Kernel, producing a new image. We have already seen a Kernel used in this paper, in our pre-processing pipeline, where we applied a Sobel Kernel to detect the edges of a sprite.

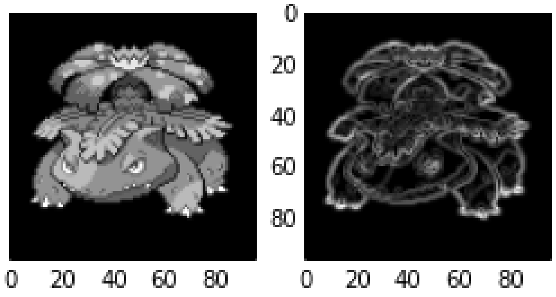
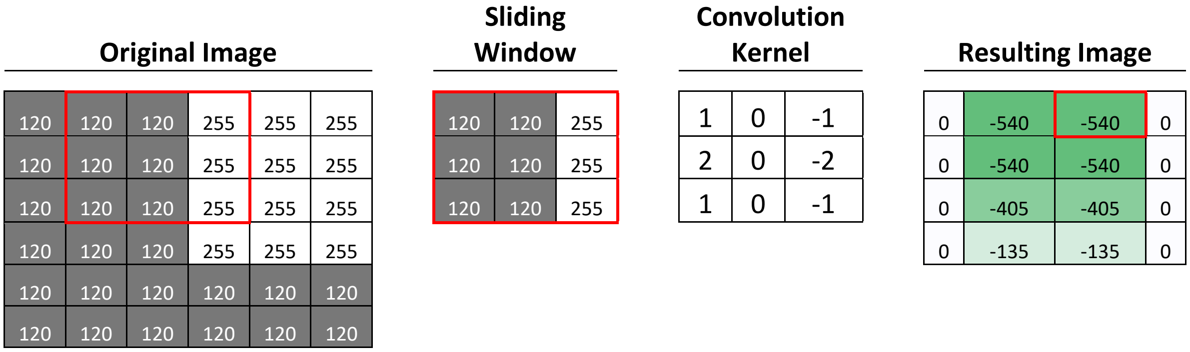


Figure 14. Sobel Kernel effect on Venusaur's sprite.

The convolution operation may be thought of as a sliding of the Kernel over our image. The values in the Kernel multiply the values below them in the image, element-wise, and the results are summed to produce a single value of the convolution over that window. (A much better explanation about the convolution operation can be found at http://setosa.io/ev/image-kernels/.) In Figure 15, we apply a vertical Sobel filter to detect sharp variations in color intensity (ranging in our grayscale images from 120 to 255).



Original Image

120	120	120	255	255	255
120	120	120	255	255	255
120	120	120	255	255	255
120	120	120	255	255	255
120	120	120	120	120	120
120	120	120	120	120	120

Sliding Window

120	120	255
120	120	255
120	120	255

Convolution Kernel

1	0	-1
2	0	-2
1	0	-1

Resulting Image

0	-540	-540	0
0	-540	-540	0
0	-405	-405	0
0	-135	-135	0

Figure 15. Convolution example. The red area highlighted in the image is being convoluted with a Vertical Edge detector, resulting in the red outlined value on the resulting matrix.

But what the heck! What do those Kernels have to do with neural networks? More than we imagine! A convolutional layer of a neural network is nothing more than a clever way to arrange the Neurons and its interconnections to achieve an architecture capable of identifying these filters through supervised learning. (Again, a way better explanation about the whole convolutional network-stuff may be found in http://cs231n.github.io/convolutional-networks/.) In our pre-processing pipeline, we used a specific Kernel because we already knew the one that would excel at the task at hand, but in a convolutional network, we let the training algorithm find those filters and combine them in subsequent layers to achieve increasingly complex features.

Our Neural Network's Architecture

I used a small-depth convolutional network for our Pokémon classification task (Fig. 16).

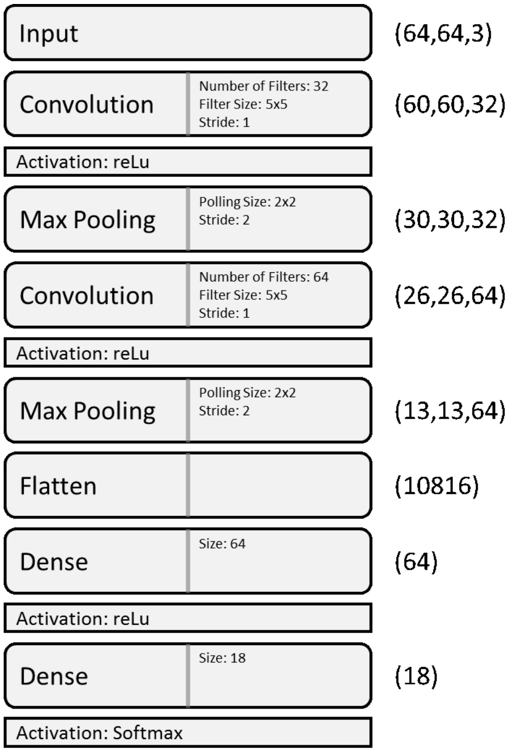
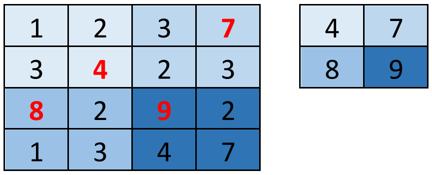


Figure 16. Architecture of the Neural Network used here.

Each layer of the image represents a layer in our convolutional network. After each layer, we obtain a state tensor that represents the output of that layer (the dimension of the tensor is listed on the right side of each layer).

A convolution layer then applies the convolution operation. In the first layer, we apply 32 kernels of size 5 to the input image, producing 32 outputs of size 60 x 60 (with each convolution the image size diminishes due to border effects).

We also use max polling layers that simply reduce a tensor region to a single one by getting its maximum value (Fig. 17). As such, after the application of a 2 x 2 max polling layer, we get a tensor that is a quarter of the size of the original.



1	2	3	7
3	4	2	3
8	2	9	2
1	3	4	7

4	7
8	9

Figure 17. Example of the max pooling operation.

At the end, we flatten our tensor to one dimension, and connect it to densely connected layers for prediction. Our final layer has size 18, the same size as the output domain.

Train and Validation

To achieve our model training we are going to split our dataset in two parts: (1) the 'training dataset' will be used by our training algorithm to learn the model parameters from the data; (2) the 'validation dataset' will be used to evaluate the model performance on unseen data. In this way, we will be able to identify overfitting issues (trust me, we are about to see a lot of overfitting[4]).

But we can't simply select a random sample of our sprites. Sprites from the same Pokémon in different games are very similar to each other, especially between games of the same generation (Fig. 18).

Figure 18. Sprites of Bird Jesus from Pokémon Platinum (left) and Diamond (right). Wait… was it the other way around?

Box 1. Performance Metrics

In this article, we used three performance metrics to assess our model performance:

(1) Accuracy: the percentage of predictions that got the right type classification of the Pokémon;

(2) Precision: the percentage of images classified as a class (type) that truly belonged to that class;

(3) Recall: the percentage of images of a class (type) that were classified as that class.

While *accuracy* enable us to get an overall quality of our model, *precision* and *recall* are used to gauge our model's prediction of each class.

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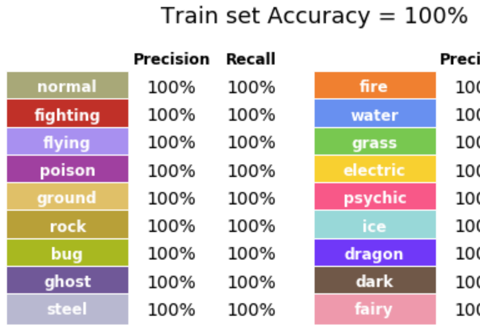
[4] Ideally, we would split our dataset in 3 separate datasets: (1) the 'training dataset' would be used to learn the model coefficients; (2) the 'validation dataset' would be used to calibrate model hyperparameters, as the learning rate of the training algorithm or even the architecture of the model, selecting the champion model; (3) the 'test dataset' would be used to evaluate the performance of the champion model. That way, we avoid introducing bias in our performance estimates due to our model selection process. As we already have a way too small dataset (and we aren't tweaking the model that much), we can disregard the test dataset.

If we randomly select sprites, we incur on the risk of tainting our validation set with sprites identical to the ones on the training set, which would lead to a great overestimation of model performance on unknown data. As such, I opted for Pokémon-wise sample. That is, I assigned the whole Pokémon to a set, instead of assigning individual sprites. That way, if Charizard is assigned to the validation set, all its sprites would follow, eliminating the risk of taint.

I used 20% of the Pokémon for the test sample, and 80% for the training set, which leaves us with 2,727 sprites for training.

First Model: Bare Bones Training

For the first try, I fed the training algorithm the original sprites, while keeping the training/ validation split. The algorithm trained over 20 epochs[5], which took about a minute in total[6]. The results obtained in this first training session are presented in Figure 19 (see also Box 1 for an explanation of the performance metrics).



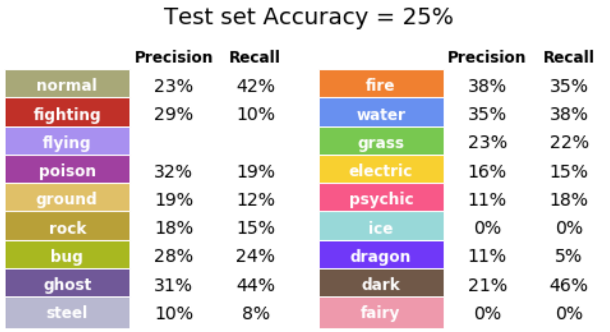
Train set Accuracy = 100%

	Precision	Recall		Precision	Recall
normal	100%	100%	fire	100%	100%
fighting	100%	100%	water	100%	100%
flying	100%	100%	grass	100%	100%
poison	100%	100%	electric	100%	100%
ground	100%	100%	psychic	100%	100%
rock	100%	100%	ice	100%	100%
bug	100%	100%	dragon	100%	100%
ghost	100%	100%	dark	100%	100%
steel	100%	100%	fairy	100%	100%

Figure 19. Performance of the training set in the first try.

Impressive! We got all the classifications right! But are those metrics a good estimation of the model performance over unseen data? Or are those metrics showing us that our models learned the training sample by heart, and will perform poorly on new data? Spoiler alert: it will. Let's get a good look at it: Figure 20 exhibits those same metrics for our validation set.

It seems that our model is indeed overfitting the training set, even if it's performing better than a random guess.



Test set Accuracy = 25%

	Precision	Recall		Precision	Recall
normal	23%	42%	fire	38%	35%
fighting	29%	10%	water	35%	38%
flying			grass	23%	22%
poison	32%	19%	electric	16%	15%
ground	19%	12%	psychic	11%	18%
rock	18%	15%	ice	0%	0%
bug	28%	24%	dragon	11%	5%
ghost	31%	44%	dark	21%	46%
steel	10%	8%	fairy	0%	0%

Figure 20. Performance of the validation set in the first try.

But wait a minute… why haven't we got any Flying type Pokémon? It turns out that there is only one monster with Flying as its primary type (Tornadus; Fig. 21), and he is included in the training set.

Figure 21. Tornadus is forever alone in the Flying type.

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[5] In machine learning context, an epoch corresponds to an iteration in which all the training data is exposed to the learning algorithm (not necessarily at once). In this case, the neural network learned from 20 successive iterations in which it saw all the data.

[6] I trained all models on Keras using the Tensorflow backend. The training was done in GPU, with a NVIDIA GTX 1080, on a PC running Ubuntu. For more details, see the companion Jupyter Notebook at GitHub (https://github.com/hemagso/Neuralmon).

Second Model: Image Augmentation

The poor performance our first model obtained for the validation set is not a surprise. Image classification, as said in the introduction, is a hard problem for computers to tackle. Our dataset is too small and does not have enough variation to enable our algorithm to learn features capable of generalization over a wider application.

To solve at least part of the problem, let's apply some image augmentation techniques. This involves applying random transformations over the training images, thus enhancing their variation. A human being would be able to identify a Pikachu, no matter its orientation (upside down, tilted to the side etc.) and we would like our model to achieve the same. As such, I applied the following range of transformations over our training dataset (Fig. 22): (1) random rotation up to 40 degrees; (2) random horizontal shifts up to 20% image width; (3) random vertical shifts up to 20% image height; (3) random zooming up to 20%; (4) reflection over the vertical axis; and (5) shear transformation over a 0.2 radians range.

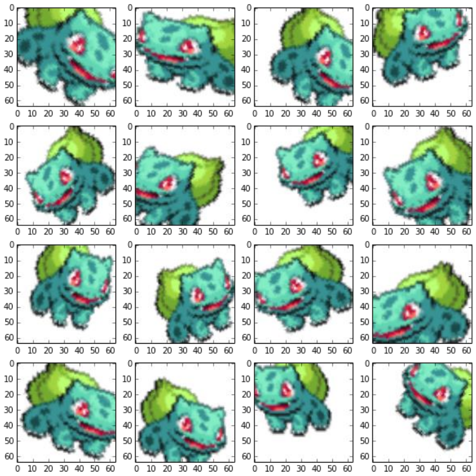
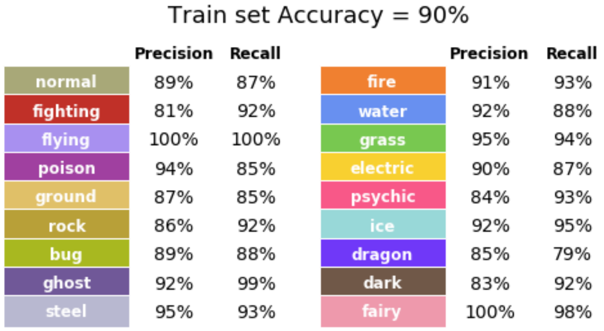


Figure 22. Images obtained through the image augmentation pipeline for one of Bulbasaur's sprites.

I applied this pipeline to all sprites in our training set, generating 10 new images for each sprite. This way, our training set was expanded to 27,270 images. But will it be enough? After training over 30 epochs (this time it took slightly longer, a little over 10 minutes in total), I obtained the following results (Fig. 23).

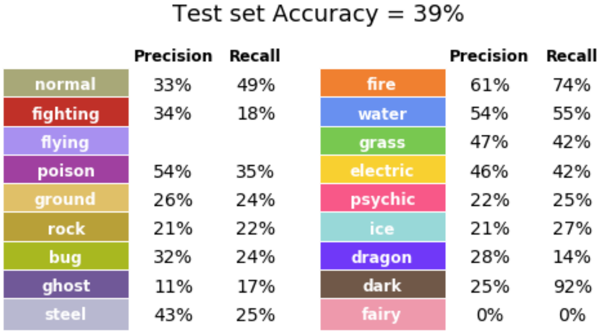


Train set Accuracy = 90%

	Precision	Recall		Precision	Recall
normal	89%	87%	fire	91%	93%
fighting	81%	92%	water	92%	88%
flying	100%	100%	grass	95%	94%
poison	94%	85%	electric	90%	87%
ground	87%	85%	psychic	84%	93%
rock	86%	92%	ice	92%	95%
bug	89%	88%	dragon	85%	79%
ghost	92%	99%	dark	83%	92%
steel	95%	93%	fairy	100%	98%

Figure 23. Performance of the training set for the second model.

Wait a minute, has our model's performance decreased? Shouldn't this image augmentation thing make my model better? Probably, but let's not start making assumptions based on our training set performance. The drop in overall performance is due to the increase in variation in our training set and this could be good news if it translates into a better performance for the validation set (Fig. 24).



Test set Accuracy = 39%

	Precision	Recall		Precision	Recall
normal	33%	49%	fire	61%	74%
fighting	34%	18%	water	54%	55%
flying			grass	47%	42%
poison	54%	35%	electric	46%	42%
ground	26%	24%	psychic	22%	25%
rock	21%	22%	ice	21%	27%
bug	32%	24%	dragon	28%	14%
ghost	11%	17%	dark	25%	92%
steel	43%	25%	fairy	0%	0%

Figure 24. Performance of the validation set for the second model.

And here we have it! Image augmentation actually helped in the model's performance. The accuracy was raised by 14 percentage points, to a total of 39%. We could keep trying to get a better model, fiddling with model hyper-parameters or trying net architectures, but we are going to stop here.

Taking a Closer Look on the Classifications

There are some things that I would like to draw your attention to. The types with greater prediction Accuracy are: Fire (61%), Water and Poison (54% each), Grass (47%), Electric (46%). The types with greater Recall (see Box 1) are: Dark (92%), Fire (74%), Water (55%), Normal (49%), Grass (42%).

It's no surprise that the three main types (Fire, Water and Grass) are among the top five in both metrics. These types have very strong affinities with colors, an information easily obtained from the images. They also are abundant types, having lots of training examples for the model to learn from.

Now let's look at some correctly and incorrectly classified Pokémon (Figs. 25 and 26, respectively).

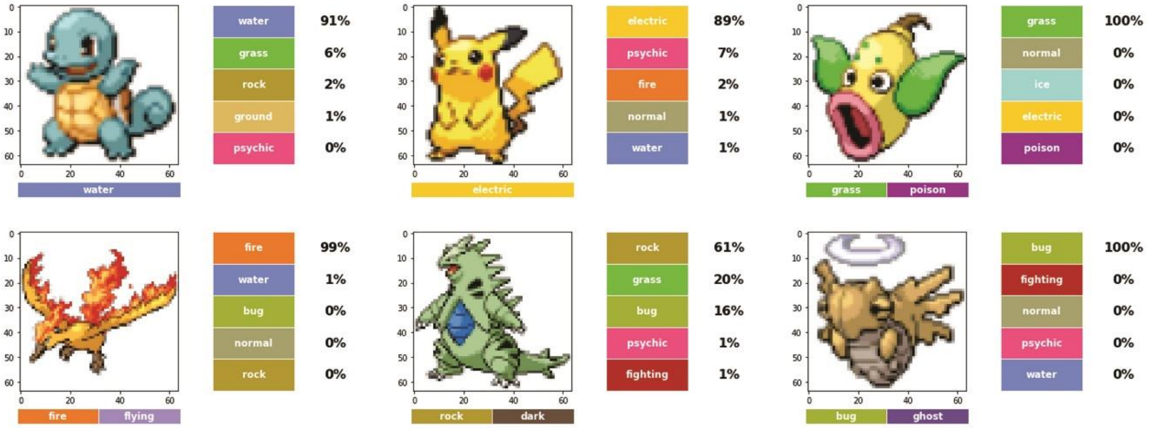


Figure 25. Some correctly classified Pokémon. Top row: Squirtle (left), Pikachu (center), Weepingbell (right). Bottom row: Moltres (left), Tyranitar (center), Shedinja (right).

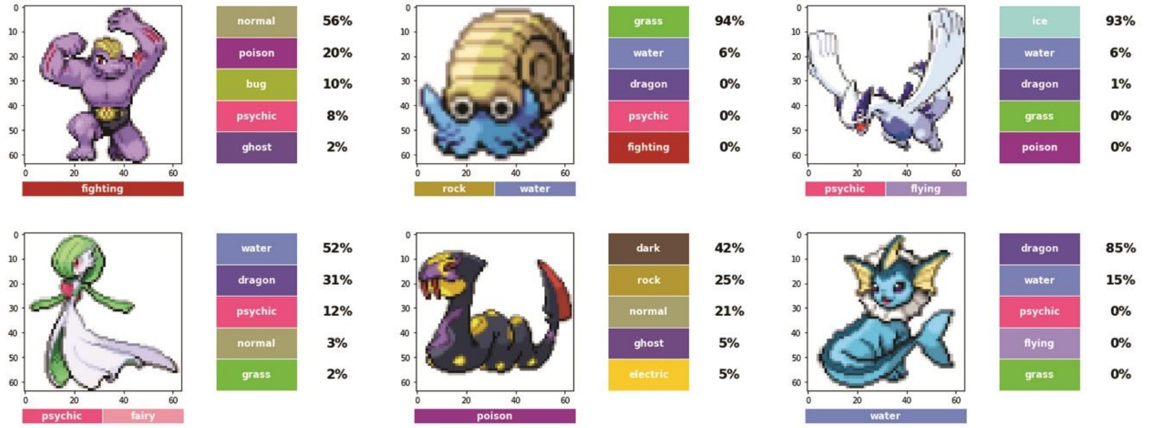


Figure 26. Some incorrectly classified Pokémon. Top row: Mochoke (left), Our Good Lord Helix (center), Lugia (right). Bottom row: Gardevoir (left), Seviper (center), Vaporeon (right).

Even in this small sample, we can see that color plays an important part in the overall classification. For example, in the incorrectly-classified Pokémon, Machoke had good chances of being a Poison type, possibly due to its purple color. Likewise, Seviper was classified as a Dark type probably due to its dark coloration.

And why is that? Well, we may never know! One of the downsides of using deep neural networks for classification is that the model is kind of a "black box". There is a lot of research going on trying to make sense of what exactly is the network searching for in the image. (I recommend that you search the Internet for "Deep Dream" for some very trippy images.)

For now, we can look at the first layer activations for some of the Pokémon and try to figure out what is it that each kernel is looking for. But as we go deeper into the network, this challenge gets harder and harder (Fig. 27).

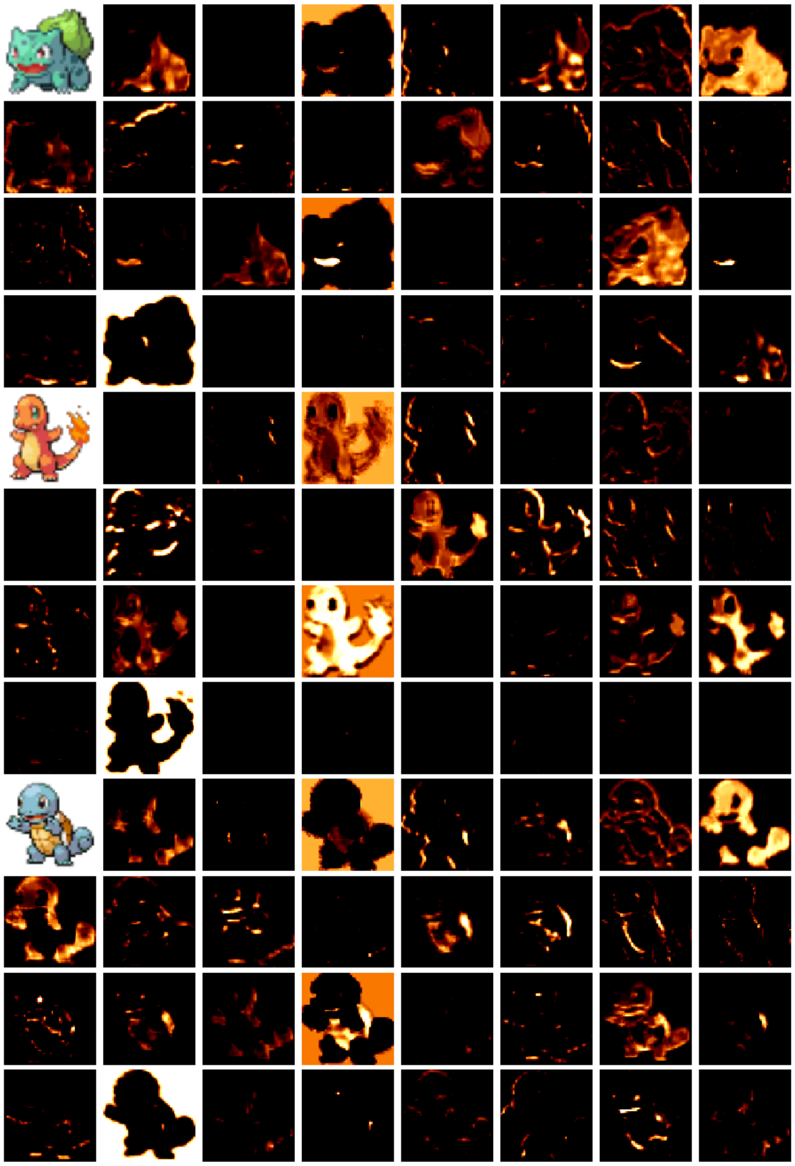


Figure 27. First layer activations (partial) for the three 1st Gen starters.

CONCLUSION

39% accuracy may not seem that impressive. But an 18-class classification problem with as little data as this is a hard one, and our model achieves a 20 percentage points gain against a Zero Rule Baseline, which is to guess the most frequent class for all Pokémon. Table 1 lists the frequencies of each class on the test set, which gives us a 19.5% accuracy for Zero Rule.

Table 1. Type frequency for the test dataset.

Type	Frequency	Percent
Water	256	19.5%
Normal	144	10.9%
Bug	127	9.7%
Grass	120	9.1%
Poison	98	7.4%
Fire	93	7.1%
Fighting	78	5.9%
Rock	74	5.6%
Ground	67	5.1%
Electric	55	4.2%
Psychic	55	4.2%
Dragon	37	2.8%
Ice	30	2.3%
Fairy	27	2.1%
Steel	24	1.8%
Ghost	18	1.4%
Dark	13	1.0%
Total	**1316**	**100.0%**

But of course, we shouldn't be measuring our machines against such clumsy methods if we expect them to one day become the dominant rulers of our planet, and computers still have a long way to go if they expect to beat my little brother in the "Pokémon Classification Challenge" someday. On the bright side, they probably already beat my old man. But this is a topic for another article…

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ABOUT THE AUTHOR

Henrique wants to be the very best, like no one ever was. When he isn't playing games, devouring sci-fi literature or writing awesome articles to an obscure geek journal on the Internet, he works a full-time job applying machine learning to the banking industry. Sadly, he got misclassified by his own creation. – Grass? Come on!?

Gotta Train 'em All

I wanna be the very best / Like no one ever was
To model them is my real test / To train them is my cause

I will travel across the data / Searching far and wide
Each model to understand / The power that's inside

Neural Net, gotta train 'em all / It's you and me / I know it's my destiny
Neural Net, oh, you're my best friend / The world we must understand
Neural Net, gotta train 'em all / A target so true / Our data will pull us through

You teach me and I'll train you
Neural Net, gotta train 'em all / Gotta train 'em all
Yeah

Journal of Geek Studies

ISSN 2359-3024

The ichthyological diversity of Pokémon

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Pokémon, or *Pocket Monsters*, was originally created for videogames, becoming a worldwide fever among kids and teenagers in the end of the 1990's and early 2000's. Currently, it is still a success, with numerous games, a TV series, comic books, movies, a Trading Card Game, toys and collectibles. Through its core products and vibrant merchandising, Pokémon took over the world, influencing pop culture wherever it landed. Despite losing some steam in the early 2010's, Pokémon is now back to its previous uproar with the release of *Pokémon GO*, an augmented reality (AR) game for smartphones. This game launched in 2016, with almost 21 million users downloading it in the very first week in the United States alone (Dorward et al., 2017). Thus, Pokémon is indubitably an icon in pop culture (Schlesinger, 1999a; Tobin, 2004).

The origin of Pokémon goes back to two role-playing video games (created by Satoshi Tajiri and released by *Nintendo* for the *Game Boy*; Kent, 2001): *Pokémon Green* and *Pokémon Red*, released in Japan in 1996. In the West, the Green version never saw the light of day, but the Red and Blue versions were released in 1998, selling together more than 10 million copies. Also in 1998, the Yellow version of the game was released, which has as its most distinct feature the possibility of having Pikachu (the most famous Pokémon) walking side by side with the player in the game. Pokémon Green, Red, Blue and Yellow are the so-called "first generation" of games in the franchise. Today, the Pokémon series is in its seventh generation, with 29 main games released, besides several spin-offs. The TV series, on the other hand, is in its sixth season, with more than 900 episodes.

The games and TV series take place in regions inhabited by many Pokémon and humans. The mission of the protagonist is to win competitions ("Pokémon battles") against gym leaders who are spread across different cities and regions. For each victory, the protagonist receives a gym badge; with eight badges, he/she is allowed to enter the Pokémon League to try and become the Champion.

For each generation, new Pokémon (and an entire new region) are introduced. In this way, the creatures have a homeland, although most can appear in other regions as well (Schlesinger, 1999b; Whitehill et al., 2016). The seven main regions are: Kanto, Johto, Hoenn, Sinnoh, Unova, Kalos and Alola.

In every region, there are numbered routes that connect cities and landmarks and in which the protagonist travels, finding the monsters in their natural habitats and interacting with other characters. These routes comprise a great range of environments, such as forests, caves, deserts, mountains, fields, seas, beaches, underwater places, mangroves, rivers and marshes, which usually display a huge diversity of Pokémon.

In addition to winning the Pokémon League, the protagonist must complete the Pokédex, a digital encyclopedia of Pokémon. In other words, the trainer must catch all the Pokémon that live in that region, registering each capture in the Pokédex. Each Pokémon has a registry number and an entry text in the Pokédex. Pokémon are usually found in nature, and may be captured with a device called "Pokéball". Pokéballs are small enough to fit in a pocket, hence the name "Pocket Monsters" (Whitehill et al., 2016).

NOT AS MONSTRUOUS AS WE THINK

In the world depicted in the games, there are 801 Pokémon, belonging to one or two of the following 18 types: Normal, Fire, Fighting, Water, Flying, Grass, Poison, Electric, Ground, Psychic, Rock, Ice, Bug, Dragon, Ghost, Dark, Steel and Fairy (Bulbapedia, 2017). Almost all Pokémon are based on animal species, some of them are based on plants or mythological creatures, and a few are based on objects. Curiously, all Pokémon are oviparous, which means they all lay eggs (their development happens inside of an egg and outside of their mother's body); of course, in the real natural world, this is a reproductive strategy of animals such as fishes, amphibians, reptiles, birds and many kinds of invertebrates (Blackburn, 1999). Moreover, Pokémon might "evolve", usually meaning they undergo some cosmetic changes, become larger and gain new powers.

In the present work, the Pokémon world was approached by analogies with the real natural world, establishing parallels with actual animals.

A remarkable group of animals represented in Pokémon is the fishes. Fishes are the largest group of vertebrates, with more than 32,000 species inhabiting marine and freshwater environments, a number that roughly corresponds to half of all described vertebrates (Nelson et al., 2016). Showing ample morphological and behavioral variety and living in most of the aquatic ecosystems of the planet, fishes are well represented in the Pokémon world, therefore offering a great opportunity for establishing parallels between the two worlds. The creators of the games not only used the morphology of real animals as a source of inspiration for the monsters, but also their ecology and behavior.

Based on these obvious connections between real fishes and Pokémon, the aim of this work is to describe the ichthyological diversity found in Pokémon based on taxonomic criteria of the classification of real fishes. Ultimately, our goal is to offer useful material for both teaching and the popularization of science.

Table 1. Taxonomic classification of the fish Pokémon. Abbreviations: Ch = Chondrichthyes; Gn = Gnathostomata; Pe = Petromyzontomorphi; Pt = Petromyzontida; Os = Osteichthyes. All images obtained from The Official Pokémon Website (2016).

Pokémon					Common Name	Species	Family	Order	Class	Super-class
Pokédex No.	Name	Image	Type	Region						
116	Horsea		Water	Kanto	Seahorse	*Hippocampus* sp.	Syngnathidae	Syngnathiformes	Os	Gn
117	Seadra		Water	Kanto	Seahorse	*Hippocampus* sp.	Syngnathidae	Syngnathiformes	Os	Gn
118	Goldeen		Water	Kanto	Goldfish	*Carassius auratus* Linnaeus, 1758	Cyprinidae	Cypriniformes	Os	Gn
119	Seaking		Water	Kanto	Goldfish	*Carassius auratus* Linnaeus, 1758	Cyprinidae	Cypriniformes	Os	Gn
129	Magikarp		Water	Kanto	Common carp	*Cyprinus carpio* Linnaeus, 1758	Cyprinidae	Cypriniformes	Os	Gn
170	Chinchou		Water / Electric	Johto	Footballfish	*Himantolophus* sp.	Himantolophidae	Lophiiformes	Os	Gn
171	Lanturn		Water / Electric	Johto	Footballfish	*Himantolophus* sp.	Himantolophidae	Lophiiformes	Os	Gn
211	Qwilfish		Water / Poison	Johto	Porcupinefish	*Diodon* sp.	Diodontidae	Tetraodontiformes	Os	Gn
223	Remoraid		Water	Johto	Remora, Suckerfish	*Remora* sp.	Echeneidae	Carangiformes	Os	Gn
226	Mantine		Water / Flying	Johto	Manta ray	*Manta birostris* Walbaum, 1792	Myliobatidae	Myliobatiformes	Ch	Gn
230	Kingdra		Water / Dragon	Johto	Common seadragon	*Phyllopteryx taeniolatus* Lacepède 1804	Syngnathidae	Syngnathiformes	Os	Gn
318	Carvanha		Water / Dark	Hoenn	Red piranha	*Pygocentrus* sp.	Serrasalmidae	Characiformes	Os	Gn
319	Sharpedo		Water / Dark	Hoenn	Shark	—	—	Carcharhiniformes	Ch	Gn
339	Barboach		Water / Ground	Hoenn	Pond loach	*Misgurnus* sp.	Cobitidae	Cypriniformes	Os	Gn
340	Whiscash		Water / Ground	Hoenn	Catfish	*Silurus* sp.	Siluridae	Siluriformes	Os	Gn
349	Feebas		Water	Hoenn	Largemouth bass	*Micropterus salmoides* Lacepède, 1802	Centrarchidae	Perciformes	Os	Gn
350	Milotic		Water	Hoenn	Oarfish	*Regalecus* sp.	Regalecidae	Lampriformes	Os	Gn
367	Huntail		Water	Hoenn	Onejaw	*Monognathus* sp.	Monognathidae	Anguilliformes	Os	Gn
368	Gorebyss		Water	Hoenn	Snipe eel	—	Nemichthyidae	Anguilliformes	Os	Gn
369	Relicanth		Water / Rock	Hoenn	Coelacanth	*Latimeria* sp.	Latimeriidae	Coelacanthiformes	Os	Gn
370	Luvdisc		Water	Hoenn	Kissing gourami	*Helostoma temminckii* Cuvier, 1829	Helostomatidae	Anabantiformes	Os	Gn
456	Finneon		Water	Sinnoh	Freshwater butterflyfish	*Pantodon buchholzi* Peters, 1876	Pantodontidae	Osteoglossiformes	Os	Gn
457	Lumineon		Water	Sinnoh	Freshwater butterflyfish	*Pantodon buchholzi* Peters, 1876	Pantodontidae	Osteoglossiformes	Os	Gn
458	Mantyke		Water / Flying	Sinnoh	Manta ray	*Manta birostris* Walbaum, 1792	Myliobatidae	Myliobatiformes	Ch	Gn

Table 1. (cont.)

Pokémon					Common Name	Species	Family	Order	Class	Super-class
Pokédex No.	**Name**	**Image**	**Type**	**Region**						
550	Basculin		Water	Unova	Piranha	—	Serrasalmidae	Characiformes	Os	Gn
594	Alomomola		Water	Unova	Sunfish	*Mola mola* Linnaeus, 1758	Molidae	Tetraodontiformes	Os	Gn
602	Tynamo		Electric	Unova	Sea lamprey	*Petromyzon marinus* Linnaeus, 1758	Petromyzontidae	Petromyzontiformes	Pt	Pe
603	Eelektrik		Electric	Unova	Sea lamprey	*Petromyzon marinus* Linnaeus, 1758	Petromyzontidae	Petromyzontiformes	Pt	Pe
604	Eelektross		Electric	Unova	Sea lamprey	*Petromyzon marinus* Linnaeus, 1758	Petromyzontidae	Petromyzontiformes	Pt	Pe
618	Stunfisk		Ground / Electric	Unova	Flatfish	—	—	Pleuronectiformes	Os	Gn
690	Skrelp		Poison / Water	Kalos	Common seadragon	*Phyllopteryx taeniolatus* Lacepède 1804	Syngnathidae	Syngnathiformes	Os	Gn
691	Dragalge		Poison / Dragon	Kalos	Leafy seadragon	*Phycodurus eques* Günther, 1865	Syngnathidae	Syngnathiformes	Os	Gn
746	Wishiwashi		Water	Alola	Pacific sardine	*Sardinops sagax* (Jenyns, 1842)	Clupeidae	Clupeiformes	Os	Gn
779	Bruxish		Water / Psychic	Alola	Reef triggerfish	*Rhinecanthus rectangulus* (Bloch & Schneider, 1801)	Balistidae	Tetraodontiformes	Os	Gn

GOTTA CATCH 'EM FISHES!

The first step of our research was a search in the Pokédex (The Official Pokémon Website, 2016) for Pokémon which were related to fishes. The criterion used was the Pokémon's morphology (resemblance to real fishes). Afterwards, the "fish Pokémon" were classified to the lowest taxonomic level (preferably species, but when not possible, genus, family or even order).

This classification of the Pokémon allowed the comparison of biological data (such as ecological, ethological, morphological traits) from Bulbapedia (2017) with the current knowledge on real fishes (*e.g.*, Nelson et al., 2016). Bulbapedia is a digital community-driven encyclopedia created in 2004 and is the most complete source regarding the pocket monsters.

The final step was a search in online scientific databases (*Fishbase*, Froese & Pauly, 2016; and *Catalog of Fishes*, Eschmeyer et al., 2016) in order to obtain the current and precise taxonomy and additional information on habitats, ecology etc. of the fish species.

In the present work, the taxonomic classification used was that proposed by Nelson et al. (2016), who consider the superclasses Petromyzontomorphi (which includes the class Petromyzontida, that is, the lampreys) and Gnathostomata (the jawed vertebrates). Gnathostomata, in turn, includes the classes Chondrichthyes (cartilaginous fishes) and Osteichthyes (bony fishes). Along with this classification, we used the classification proposed by the database ITIS (Integrated Taxonomic Information System, 2016) for comparison at all taxonomic levels. Following identification, the "fish Pokémon" were described regarding their taxonomic and ecological diversity.

POCKET FISHES

As a result of our search, 34 fish Pokémon were identified (circa 4% of the total 801 Pokémon; Table 1) and allocated in two superclasses, three classes, eighteen orders, twenty families and twenty-two genera. Eighteen of the 34 fish Pokémon (circa 53%) could be identified to the species level (Table 2). The features of the real fishes which probably inspired the creation of the Pokémon and other relevant information are described below for each species. To enrich the comparisons, images of the Pokémon (obtained from the Pokédex of The Official Pokémon Website; www.pokemon.com) and of the real fishes (illustrations by one of us, C.B.P. Eirado-Silva) follow the descriptions.

Table 2. Taxonomic diversity of the fish Pokémon.

Taxon	n	%
Species	18	52.94
Genus	22	88.23
Family	20	94.12
Order	18	100
Class	3	100
Superclass	2	100

Horsea and Seadra

Species: *Hippocampus* sp.; **Common name:** seahorse.

The Pokémon Horsea and Seadra (Fig. 1), which debuted in the first generation of the franchise, were based on seahorses. The long snout, ending in a toothless mouth (Foster & Vincent, 2004), the prehensile, curved tail (Rosa et al., 2006) and the salient abdomen are features of the real fishes present in these Pokémon. Seahorses belong to the genus *Hippocampus*, presently composed of 54 species (Nelson et al., 2016). The males have a pouch in their bellies where up to 1,000 eggs are deposited by the females. In this pouch, the eggs are fertilized and incubated for a period ranging from 9 to 45 days (Foster & Vincent, 2004). Due to overfishing for medicinal and ornamental purposes, as well habitat destruction, about 33 species of seahorses are considered threatened (Rosa et al., 2007, Castro et al., 2008; Kasapoglu & Duzgunes, 2014).

Figure 1. Horsea, Seadra and *Hippocampus* sp.

Goldeen and Seaking

Species: *Carassius auratus*; **Common name:** goldfish.

Goldeen and Seaking (Fig. 2) were based on the goldfish. This species is one of the most common ornamental fishes worldwide (Soares et al., 2000; Moreira et al., 2011) and it is widely used in studies of physiology and reproduction due to its docile behavior and easy acclimatization to artificial conditions (Bittencourt et al., 2012; Braga et al., 2016). The resemblance between the goldfish and the Pokémon include morphological features, such as the orange/reddish color and the long merged fins, and the name "Goldeen". The name Seaking, on the other hand, may be a reference to another common name of the species, "kinguio", from the Japanese "kin-yu" (Ortega-Salas & Reyes-Bustamante, 2006).

Magikarp

Species: *Cyprinus carpio*; **Common name:** common carp.

Possibly the most famous fish Pokémon, Magikarp (Fig. 3) was based on a common carp, a species present in Europe, Africa and Asia, widely used in pisciculture due to its extremely easy acclimatization to many freshwater environments and the high nutritional value of its meat (Stoyanova et al., 2015; Mahboob et al., 2016; Voigt et al., 2016). In some regions of the planet, such as Brazil, the common carp is considered an invasive species, as it was inadvertently released in the wild and poses a threat to the native aquatic fauna (Smith et al., 2013; Contreras-MacBeath et al., 2014).

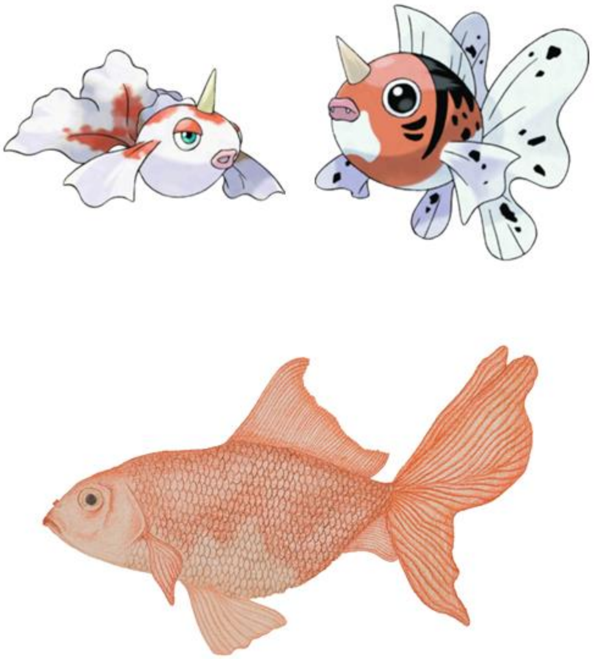

Figure 2. Goldeen, Seaking and *Carassius auratus*.

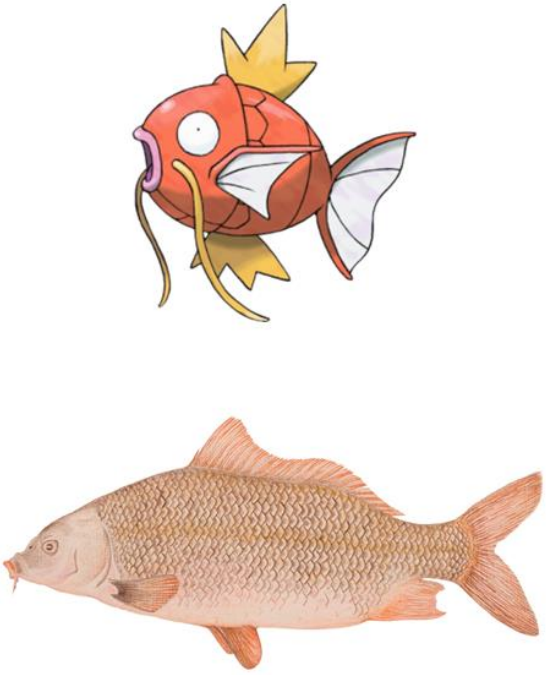

Figure 3. Magikarp and *Cyprinus carpio*.

The shared traits between the Pokémon and the real fish are many: the rounded mouth, the lips, the strong orange color and the presence of barbels ("whiskers") (Nelson et al., 2016). In China, the common carp is praised as an animal linked to honor and strength, due of its ability to swim against the current; an ancient legend tells about carps that swim upstream, entering through a portal and transforming into dragons (Roberts, 2004). In Pokémon, Magikarp evolves into Gyarados, which resembles a typical Chinese dragon.

Chinchou and Lanturn

Species: *Himantolophus* sp.; **Common name:** footballfish.

Chinchou and Lanturn (Fig. 4) were based on fishes of the genus *Himantolophus*, a group of deep-sea fishes found in almost all oceans living in depths up to 1,800 meters (Klepadlo et al., 2003; Kharin, 2006). These fishes are known as footballfishes, a reference to the shape of their bodies. Fishes of this genus have a special modification on their dorsal fin that displays bioluminescence (the ability to produce light through biological means; Pietsch, 2003), which is used to lure and capture prey (Quigley, 2014). Bioluminescence was the main inspiration for these Pokémon, which have luminous appendages and the Water and Electric types. The sexual dimorphism (difference between males and females) is extreme in these fishes: whilst females reach up to 47 cm of standard-length (that is, body length excluding the caudal fin), males do not even reach 4 cm (Jónsson & Pálsson, 1999; Arronte & Pietsch, 2007).

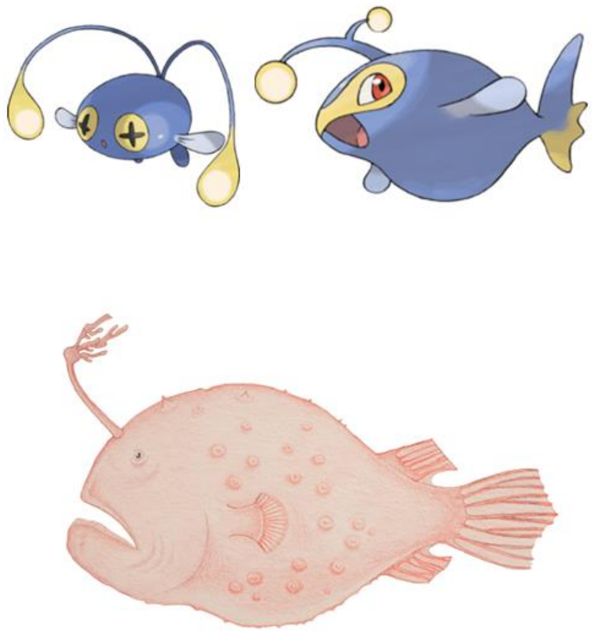

Figure 4. Chinchou, Lanturn and *Himantolophus* sp.

Qwilfish

Species: *Diodon* sp.; **Common name:** porcupinefish.

Qwilfish (Fig. 5) was based on porcupinefishes, more likely those of the genus *Diodon*, which present coloring and spines most similar to this Pokémon. Besides the distinctive hard, sharp spines (Fujita et al., 1997), porcupinefishes have the ability to inflate as a strategy to drive off predators (Raymundo & Chiappa, 2000). As another form of defense, these fishes possess a powerful bacterial toxin in their skin and organs (Lucano-Ramírez et al., 2011; Ravi et al., 2016). Accordingly, Qwilfish has both Water and Poison types.

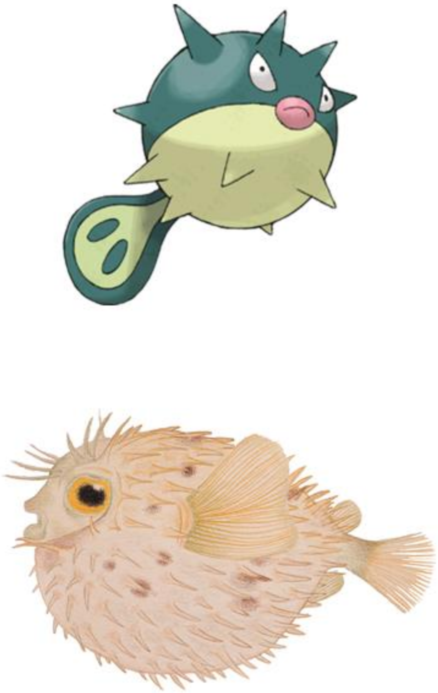

Figure 5. Qwilfish and *Diodon* sp.

Remoraid

Species: *Remora* sp.; **Common names:** remora, suckerfish.

Remoraid was based on a remora (Fig. 6), a fish with a suction disc on its head that allows its adhesion to other animals such as turtles, whales, dolphins, sharks and manta rays (Fertl & Landry, 1999; Silva & Sazima, 2003; Friedman et al., 2013; Nelson et al., 2016). This feature allows the establishment of a commensalisc or mutualisc relationship of transportation, feeding and protection between the adherent species and its "ride" (Williams et al., 2003; Sazima & Grossman, 2006). The similarities also include the name of the Pokémon and the ecological relationship they have with other fish Pokémon: in the same way remoras keep ecological relationships with rays, Remoraid does so with Mantyke and Mantine (Pokémon based on manta rays; see below).

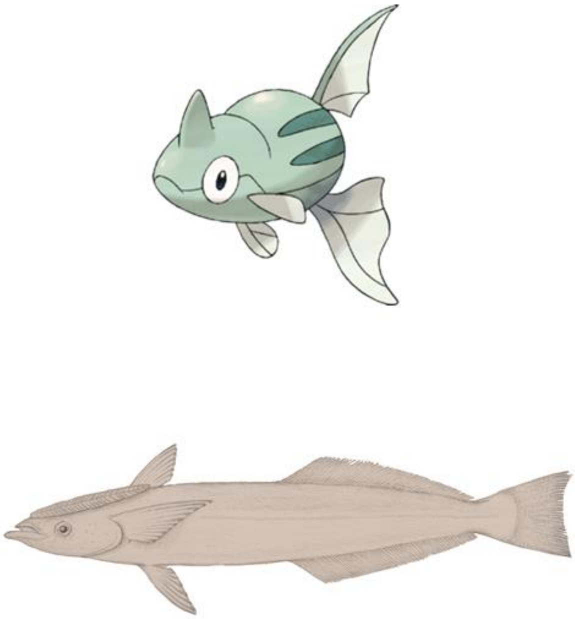

Figure 6. Remoraid and *Remora* sp.

Mantyke and Mantine

Species: *Manta birostris*; **Common name:** manta ray.

The Pokémon Mantyke and its evolved form Mantine (Fig. 7) were probably based on manta rays of the species *Manta birostris*, which inhabits tropical oceans (Duffy & Abbot, 2003; Dewar et al., 2008) and can reach more than 6 meters of wingspan, being the largest species of ray in existence (Homma et al., 1999; Ari & Correia, 2008; Marshall et al., 2008; Luiz et al., 2009; Nelson et al., 2016). The similarities between the Pokémon and the real fish are: the body shape, the color pattern, the large and distinctive wingspan and even the names.

Figure 7. Mantine, Mantyke and *Manta birostris*.

Kingdra and Skrelp

Species: *Phyllopteryx taeniolatus*; **Common name:** common seadragon.

Kingdra and Skrelp (Fig. 8) were based on the common seadragon. The resemblances between these Pokémon and the real fish species include the leaf-shaped fins that help the animals to camouflage themselves in the kelp "forests" they inhabit (Sanchez-Camara et al., 2006; Rossteuscher et al., 2008; Sanchez-Camara et al., 2011), and the long snout. Also, the secondary type of Kingdra is Dragon. Although both are based on the common seadragon, Kingdra and Skrelp are not in the same "evolutionary line" in the game.

Common seadragons, as the seahorses mentioned above, are of a particular interest to conservationists, because many species are vulnerable due to overfishing, accidental capture and habitat destruction (Foster & Vincent, 2004; Martin-Smith & Vincent, 2006).

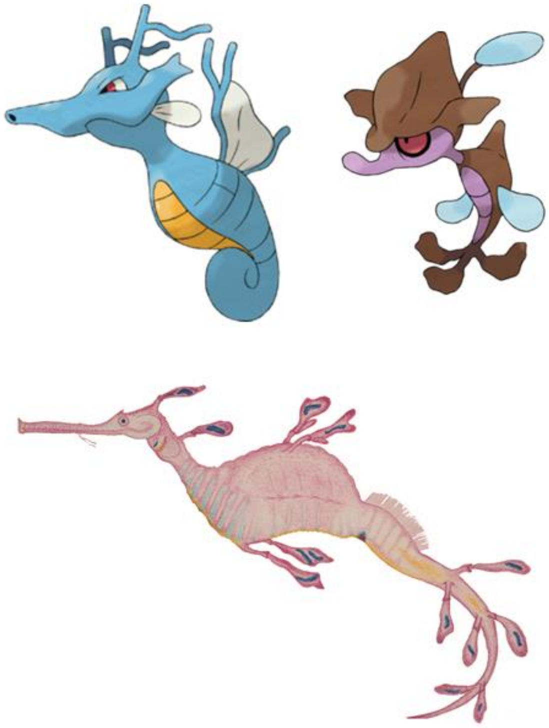

Figure 8. Kingdra, Skrelp and *Phyllopteryx taeniolatus*.

Carvanha

Species: *Pygocentrus* sp.; **Common name:** red piranha.

Piranhas of the genus *Pygocentrus* possibly were the inspiration for the creation of Carvanha (Fig. 9), a Pokémon of voracious and dangerous habits. The main feature shared by the real fish and the Pokémon is the color pattern: bluish in the dorsal and lateral areas, and reddish in the ventral area (Piorski et al., 2005; Luz et al., 2015).

It is worthwhile pointing out that, despite what is shown in movies and other media, piranhas do not immediately devour their prey;

instead, they tear off small pieces, bit by bit, such as scales and fins (Trindade & Jucá-Chagas, 2008; Vital et al., 2011; Ferreira et al., 2014).

Figure 9. Carvanha and *Pygocentrus* sp.

Sharpedo

Order: Carcharhiniformes; **Common name:** shark.

Sharpedo (Fig. 10), according to its morphological traits (elongated fins), was possibly based on sharks of the order Carcharhiniformes, the largest group of sharks, with 216 species in 8 families and 48 genera. Fishes in this order are common in all oceans, in both coastal and oceanic regions, and from the surface to great depths (Gomes et al., 2010). Several species of Carcharhiniformes are in the IUCN’s (International Union for Conservation of Nature) endangered species list (a.k.a. “Red List”) due to overfishing, as their fins possess high commercial value (Cunningham-Day, 2001).

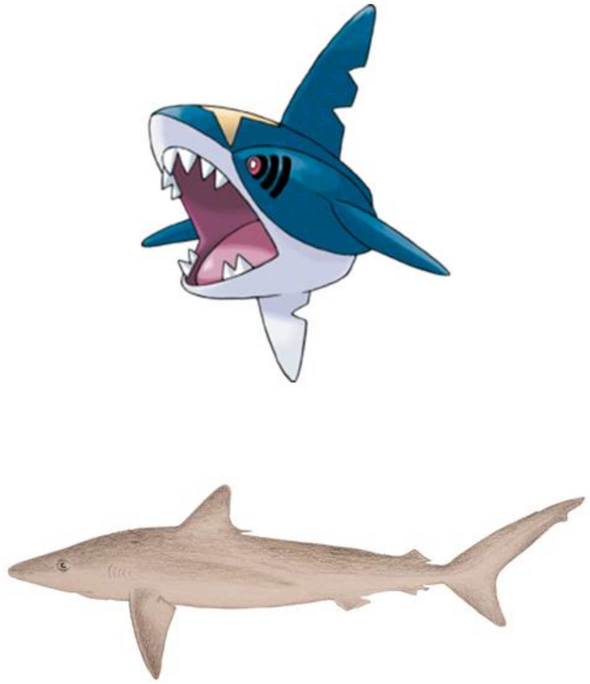

Figure 10. Sharpedo and a carcharhiniform shark.

Barboach

Species: *Misgurnus* sp.; **Common name:** pond loach.

Barboach (Fig. 11) is likely based on fishes of the genus *Misgurnus*, natively found in East Asia (Nobile et al., 2017) but introduced in several countries (Gomes et al., 2011). These animals, like *M. anguillicaudatus* Cantor, 1842, are used as ornamental fishes and in folk medicine (Woo Jun et al., 2010; Urquhart & Koetsier, 2014). The shared similarities between the Pokémon and the pond loach include morphological features, such as the elongated body, oval fins and the presence of barbels (Nelson et al., 2016). The resemblance also extends itself to behavior, such as the habit of burying in the mud (Zhou et al., 2009; Kitagawa et al., 2011) and using the barbels to feel the surroundings (Gao et al., 2014). The secondary type of Barboach, Ground, alongside the ability to feel vibrations in the substrate, seem to be a reference to the behavior of the real fishes.

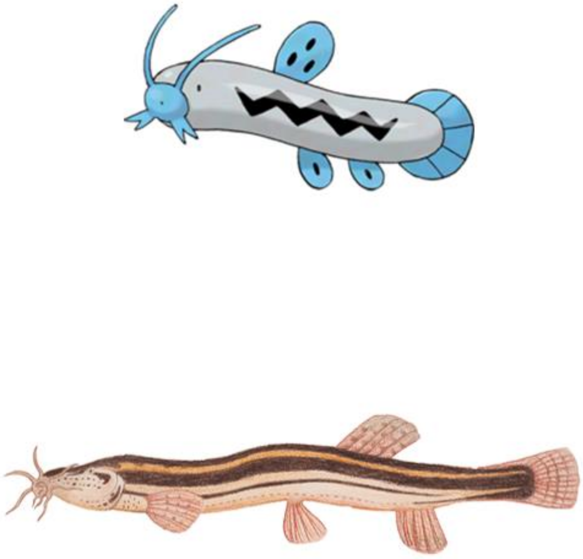

Figure 11. Barboach and *Misgurnus* sp.

Whiscash

Species: *Silurus* sp.; **Common name:** catfish.

Whiscash (Fig. 12) was based on the Japanese mythological creature Namazu, a gigantic catfish that inhabits the underground realm and is capable of creating earthquakes (Ashkenazi, 2003). Namazu also names the Pokémon in the Japanese language (“*Namazun*”). In Japan, fishes of the genus *Silurus* are usually associated with this mythological creature and even the common name of these fishes in that country is “*namazu*” (Yuma et al., 1998; Malek et al., 2004). In addition, the physical traits of the *Silurus* catfishes also present in Whiscash are the long barbels (or “whiskers”, hence the name Whiscash) and the robust body (Kobayakawa, 1989; Kiyohara & Kitoh, 1994). In addition to the Water type, Whiscash is also Ground type, which is related to Namazu’s fantastic ability of creating earthquakes.

Figure 12. Whiscash and *Silurus* sp.

Feebas

Species: *Micropterus salmoides*; **Common name:** largemouth bass.

The Pokémon Feebas (Fig. 13), a relatively weak fish (as its name implies), was possibly based on a largemouth bass, a freshwater fish native to North America (Hossain et al., 2013). The species was introduced in many countries and is often considered a threat to the native fauna (Welcomme, 1992; Hickley et al., 1994; Godinho et al., 1997; García-Berthou, 2002). Similarities between Feebas and the largemouth bass include the large, wide mouth and the brownish coloration, with darker areas (Brown et al., 2009).

Figure 13. Feebas and *Micropterus salmoides*.

Milotic

Species: *Regalecus* sp.; **Common name:** oarfish.

Often praised as the most beautiful Pokémon of all (Bulbapedia, 2017), Milotic (Fig. 14) certainly lives up to its title. Their long reddish eyebrows were based on the first elongated rays of the dorsal fin of *Regalecus* species (Nelson et al., 2016), which also share the reddish color of the dorsal fin (Carrasco-Águila et al., 2014). Other similarities between the oarfish and the Pokémon are the elongated body (some oarfishes can grow larger than 3.5 m) and the spots scattered on the body (Chavez et al., 1985; Balart et al., 1999; Dulčić et al., 2009; Ruiz & Gosztonyi, 2010).

Figure 14. Milotic and *Regalecus* sp.

Huntail

Species: *Monognathus* sp.; **Common name:** onejaw.

Probably based on fishes of the genus *Monognathus*, which have a large mandible and a long dorsal fin (Nelson et al., 2016), Huntail (Fig. 15) is one of the possible evolutionary results of the mollusk Pokémon Clamperl (the other possibility is Gorebyss; see below). According to Raju (1974), fishes of the genus *Monognathus* live in great depths and have a continuous dorsal fin that ends in an urostyle ("*uro*" comes from the Greek language and means "tail", an element also present in the Pokémon's name).

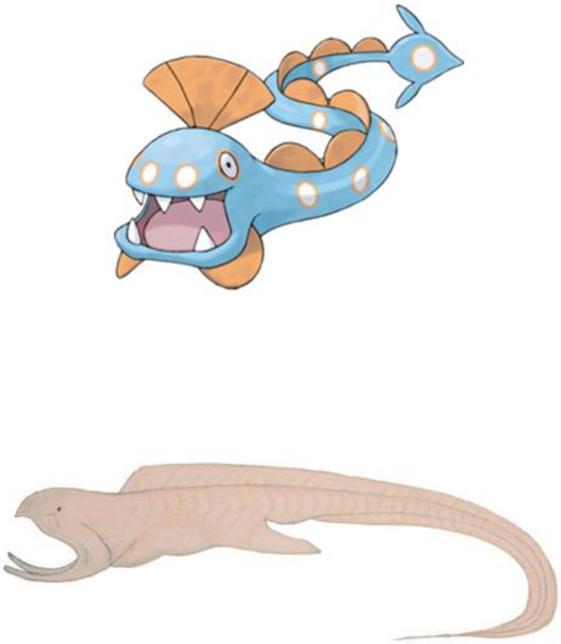

Figure 15. Huntail and *Monognathus* sp.

Gorebyss

Family: Nemichthyidae; **Common name:** snipe eel.

The serpentine body and the thin beak-shaped jaw of Gorebyss (Fig. 16) are features of fishes belonging to the family Nemichthyidae (Nielsen & Smith, 1978). These fishes inhabit tropical and temperate oceans and can be found in depths up to 4,000 meters, in the so-called "abyssal zone" (Cruz-Mena & Anglo, 2016). The Pokémon's name may be a reference to such habitat.

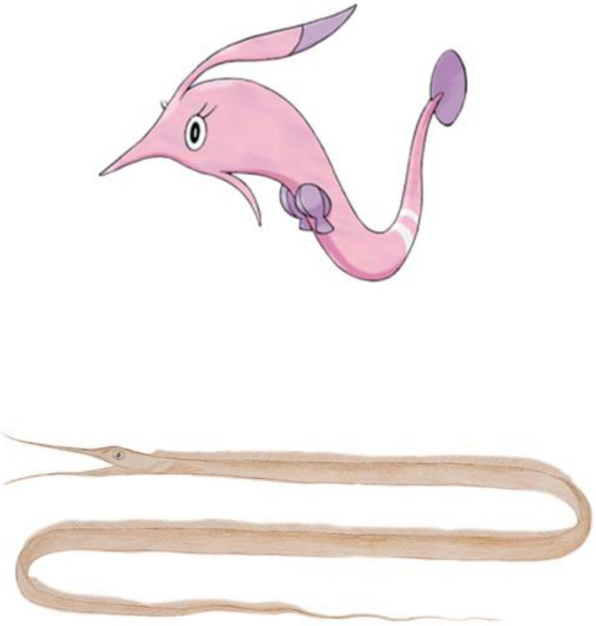

Figure 16. Gorebyss and a nemichthyid fish.

Relicanth

Species: *Latimeria* sp.; **Common name:** coelacanth.

Relicanth (Fig. 17) was based on the coelacanth. The brown coloration, the lighter patches on the body (Benno et al., 2006) and the presence of paired lobed fins (Zardoya & Meyer, 1997) are traits of both the real fish and the Pokémon. It was believed that coelacanths went extinct in the Late Cretaceous, but they were rediscovered in 1938 in the depths off the coast of South Africa (Nikaido et al., 2011). Therefore, the only two living species *L.*

chalumnae Smith, 1939 and *L. menadoensis* Pouyaud et al., 1999 are known as "living fossils" (Zardoya & Meyer, 1997). Probably for this reason, Relicanth belongs to the Water and Rock types (the “fossil Pokémon" are all Rock-type).

Figure 17. Relicanth and *Latimeria* sp.

Luvdisc

Species: *Helostoma temminckii*; **Common name:** kissing gourami.

The silver-pinkish coloration, the peculiar mouth formed by strong lips and the habit of "kissing" other individuals of their species (which is actually a form of aggression!) are features of the kissing gourami (Sterba 1983; Sousa & Severi 2000; Sulaiman & Daud, 2002; Ferry et al., 2012) that are also seen in Luvdisc (Fig. 18). *Helostoma temminckii* is native to Thailand, Indonesia, Java, Borneo, Sumatra and the Malay Peninsula (Axelrod et al., 1971), but due to its use an ornamental fish and the irresponsible handling by fishkeepers, it has been introduced in other parts of the world (Magalhães, 2007).

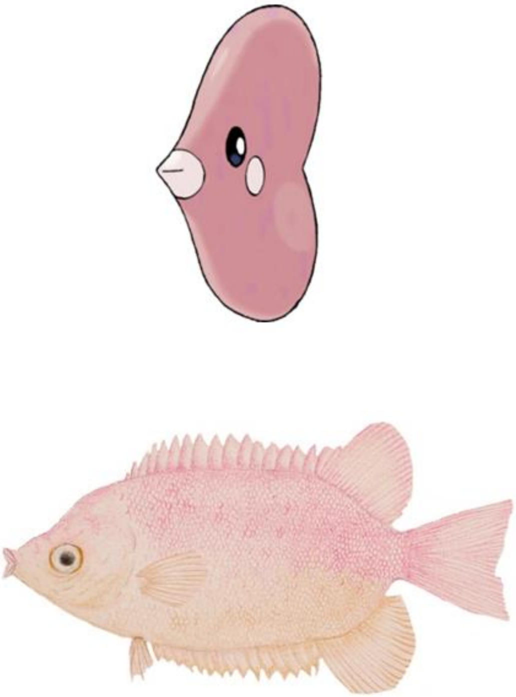

Figure 18. Luvdisc and *Helostoma temminckii*.

Finneon and Lumineon

Species: *Pantodon buchholzi*; **Common name:** freshwater butterflyfish.

Finneon and Lumineon (Fig. 19) were probably based on the freshwater butterflyfish. Finneon has a caudal fin in the shape of a butterfly and Lumineon, like *Pantodon buchholzi*, has large pectoral fins (Nelson et al., 2016) resembling the wings of a butterfly (hence the popular name of the species). Butterflyfishes are found in West African lakes

(Greenwood & Thompson, 1960); their backs are olive-colored while their ventral side is silver, with black spots scattered throughout the body; their fins are pink with some purplish spots (Lévêque & Paugy, 1984). Both Pokémon have color patterns that resemble the freshwater butterflyfish.

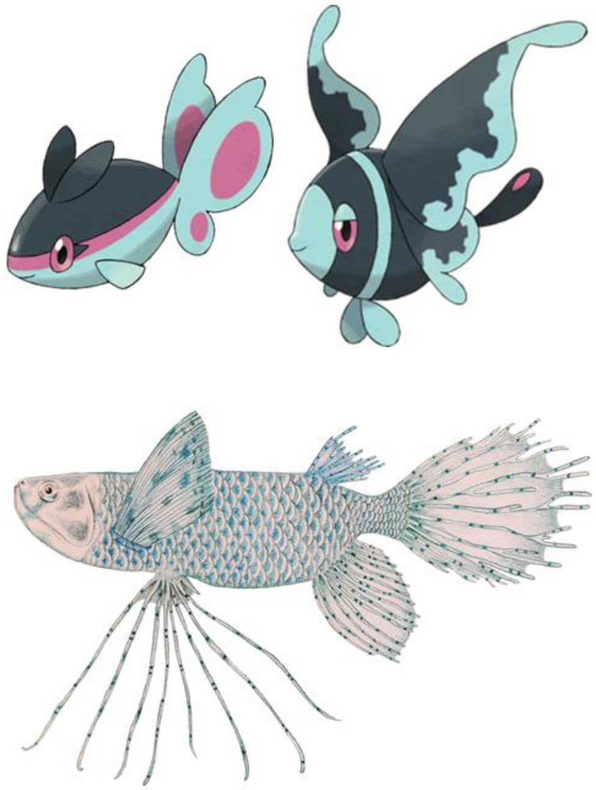

Figure 19. Finneon, Lumineon and *Pantodon buchholzi*.

Basculin

Family: Serrasalmidae; **Common name:** piranha.

The two forms of the Pokémon Basculin (Fig. 20) seem to have been inspired on fishes from the Serrasalmidae family, such as piranhas. Basculin, like these fishes, has a tall body and conical teeth (Baumgartner et al., 2012). Piranhas are predators with strong jaws that inhabit some South American rivers. Curiously, they are commonly caught by local subsistence fishing (Freeman et al., 2007).

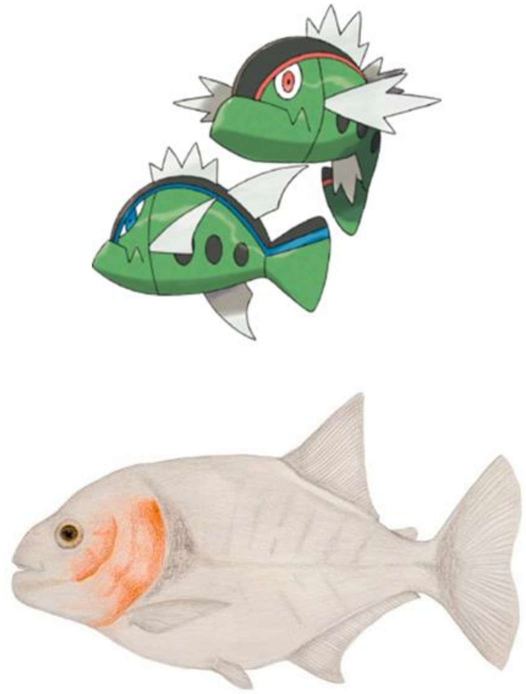

Figure 20. Basculin's two forms and a serrasalmid fish.

Alomomola

Species: *Mola mola*; **Common name:** sunfish.

The very name of this Pokémon is evidence that it was inspired on *Mola mola*, the sunfish (Fig. 21). Moreover, Alomomola, just like the sunfish, has a circular body with no caudal fin (Pope et al., 2010). The sunfish is the largest and heaviest bony fish in the world, weighting more than 1,500 kg (Freesman & Noakes, 2002; Sims et al., 2009). They inhabit the Atlantic and Pacific Oceans, feeding mainly on zooplankton (Cartamil & Lowe, 2004; Potter & Howell, 2010).

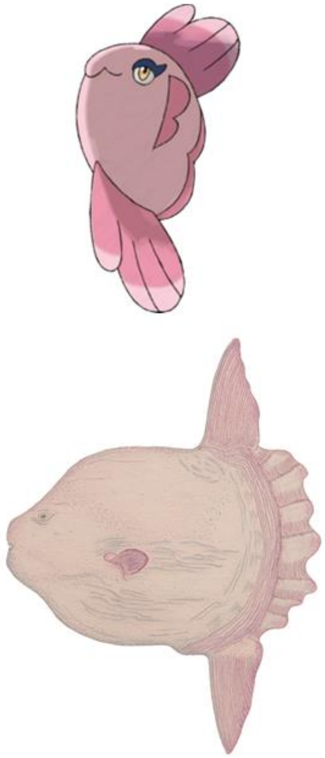

Figure 21. Alomomola and *Mola mola*.

Tynamo, Eelektrik and Eelektross

Species: *Petromyzon marinus*; **Common name:** sea lamprey.

The evolutionary line Tynamo, Eelektrik and Eelektross (Fig. 22) was probably inspired by the life cycle of the sea lamprey, *Petromyzon marinus*: Tynamo represents a larval stage, Eelektrik a juvenile, and Eelektross an adult. As a larva, the sea lamprey inhabits freshwater environments and, after going through metamorphosis, the juvenile migrates to the ocean, where they start to develop hematophagous ("blood-sucking") feeding habits (Youson, 1980; Silva et al., 2013). Eelektrik and Eelektross, like the sea lamprey, have a serpentine body and a circular suction cup-mouth with conical teeth. In addition, the yellow circles on the side of these Pokémon resemble the gill slits of lampreys (which are of circular shape) or the marbled spots of *P. marinus* (Igoe et al., 2004).

It is worth mentioning that Eelektrik and Elektross also seem to possess name and characteristics (Electric type and serpentine body with yellow spots) inspired by the electric eel (*Electrophorus electricus* Linnaeus, 1766), a fish capable of generating an electrical potential up to 600 volts, making it the greatest producer of bioelectricity in the animal kingdom (Catania, 2014). However, a remarkable characteristic of Eelektrik and Eelektross is the jawless mouth structure of the superclass Petromyzontomorphi species. The electric eel has a jaw and thus belongs to the superclass Gnathostomata (jawed vertebrates) (Gotter et al., 1998).

Figure 22. Tynamo, Eelektrik, Eelektross and *P. marinus*.

Stunfisk

Order: Pleuronectiformes; **Common name:** flatfish.

Flattened and predominantly brown in color, Stunfisk (Fig. 23) appears to have been based on fishes of the order Pleuronectiformes. Popularly known as flatfishes, these animals have both eyes on the same side of the head and stay most of their lives buried and camouflaged on sandy and muddy substrates of almost every ocean, feeding on fishes and benthic invertebrates (Sakamoto, 1984; Kramer, 1991; Gibb, 1997). It is likely that the primary type of Stunfisk, Ground, is based on the close relationship between pleuronectiform fishes and the substrate they live in. Species of this group are very valuable for the fishing industry (Cooper & Chapleau, 1998).

Figure 23. Stunfisk and a pleuronectiform fish.

Dragalge

Species: *Phycodurus eques*; **Common name:** leafy seadragon.

Dragalge (Fig. 24), a Pokémon belonging to the Poison and Dragon types, was based on a leafy seadragon. This species is found in Australia and it is named after its appearance: this fish has appendages throughout its body that resemble leaves (Larson et al., 2014). This feature, also present in the Pokémon, allows the leafy seadragon to camouflage itself among algae (Wilson & Rouse, 2010). Dragalge is the evolved form of Skrelp, a Pokémon based on a common seadragon (see above).

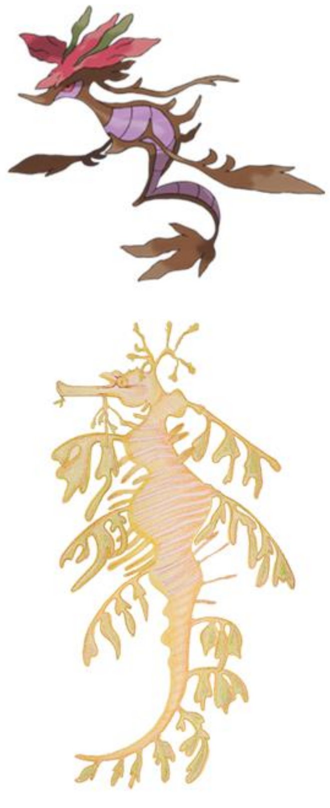

Figure 24. Dragalge and *Phycodurus eques*.

Wishiwashi

Species: *Sardinops sagax*; **Common name:** Pacific sardine.

Wishiwashi (Fig. 25) was probably based on the Pacific sardine, a pelagic fish with high commercial value and quite abundant along the California and Humboldt Currents (Coleman, 1984; Gutierrez-Estrada et al., 2009; Demer et al., 2012; Zwolinski et al., 2012). The lateral circles of the Pokémon are a reference to the dark spots present on the lateral areas of the real fish (Paul et al., 2001). Furthermore, Wishiwashi has the ability to form a large school, just as sardines do (Emmett et al., 2005; Zwolinski et al., 2007).

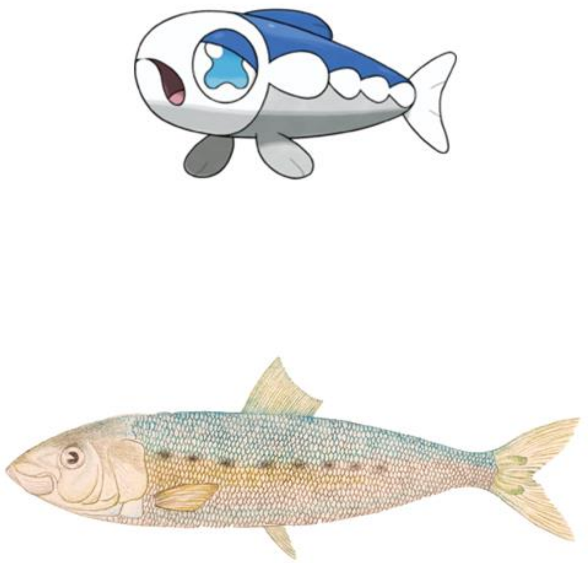

Figure 25. Wishiwashi and *Sardinops sagax*.

Another parallel is the geographic location: the Pokémon belongs to Alola, a fictional region based on Hawaii, and *S. sagax* is one of the most common sardines in the Eastern Pacific Ocean. From the mid-1920's to the mid-1940's, for example, *S. sagax* supported one of the largest fisheries in the world. The stock collapsed in the late 1940's, but in the 1990's it started to recover (McFarlane et al., 2005).

Bruxish

Species: *Rhinecanthus rectangulus*; **Common name:** reef triggerfish.

Bruxish (Fig. 26) was probably inspired by the species *Rhinecanthus rectangulus*, the reef triggerfish of the Hawaiian reefs and other tropical regions (Kuiter & Debelius, 2006; Dornburg et al., 2008). Bruxish has powerful jaws, just like the reef triggerfishes that prey upon a wide variety of invertebrates, such as hard-shelled gastropods, bivalves, echinoderms and crustaceans (Wainwright & Friel, 2000; Froese & Pauly, 2016).

Figure 26. Bruxish and *Rhinecanthus rectangulus*.

Besides the strong jaw, the overall body shape and the flashy coloring, another parallel can be seen: this Pokémon is an inhabitant of the Alola region (the Pokémon version of Hawaii) and *R. rectangulus* is actually the state symbol fish of the Hawaiian archipelago (Kelly & Kelly, 1997).

POCKET FISHES UNDER SCRUTINY

The majority of the identified Pokémon (85.29%) is, expectedly, Water-type. A large portion of them (29.41%) was introduced for the first time in the third generation of the franchise, in the Hoenn region.

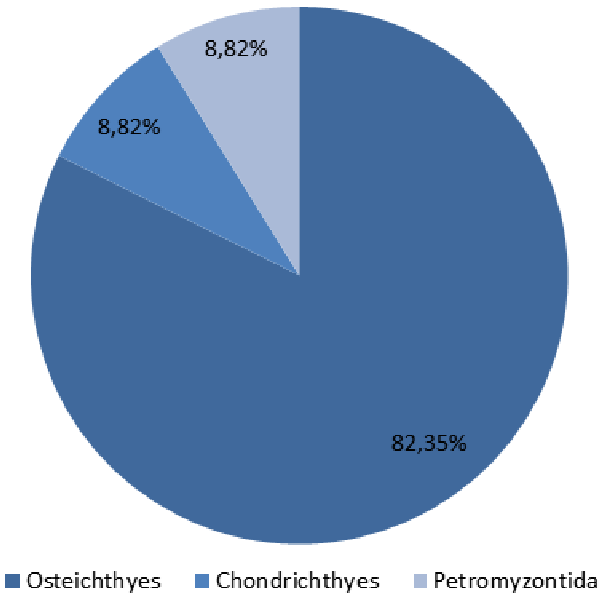

Figure 27. Representativeness of fish classes in *Pokémon*.

Only three fish Pokémon were classified in the superclass Petromyzontomorphi (8.82%): the lamprey-like Tynamo, Eelektrik and Eelektross, all of them belonging to the same evolutionary line. In the superclass Gnathostomata, the class Osteichthyes is represented by the highest number of Pokémon: 28 in total (82.35%, Fig. 27). Inside this class, the most representative groups were the order Syngnathiformes (14.71%, Fig. 28), family Syngnathidae (15.63%, Fig. 29) and the genus *Petromyzon* (10.00%, Fig. 30).

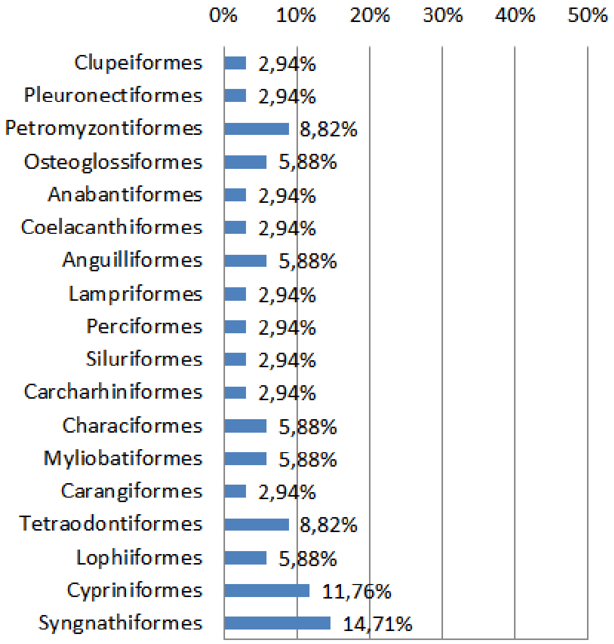

Figure 28. Representativeness of fish orders in *Pokémon*.

Most of the real fishes on which the Pokémon were based (55.88%, Fig. 31) live in marine environments, followed by freshwater (continental water environments, 32.35%) and finally, brackish water (estuarine environments, 11.76%).

The "fish" species found in the Pokémon world consists of a considerable portion of the ichthyological diversity in our world. According to Nelson et al. (2016), the Osteichthyes class corresponds to 96.1% of all vertebrate fish species (30,508 species), followed by the Condrichthyes with 3.76% (1,197 species) and the Petromyzontida with just 0.14% (46 species). In *Pokémon*, the proportions of taxa (taxonomic group) that inspired the creatures follow a roughly similar distribution: within the 26 taxa in which the evolutionary families of the Pokémon were based, 23 are Osteichthyes class (88.46%), two are Condrichthyes (7.7%) and one is Petromyzontida (3.84%). If the games follow a pattern of introducing more fish Pokémon over time, it is expected that these proportions will gradually become more equivalent as each new generation of the franchise is released.

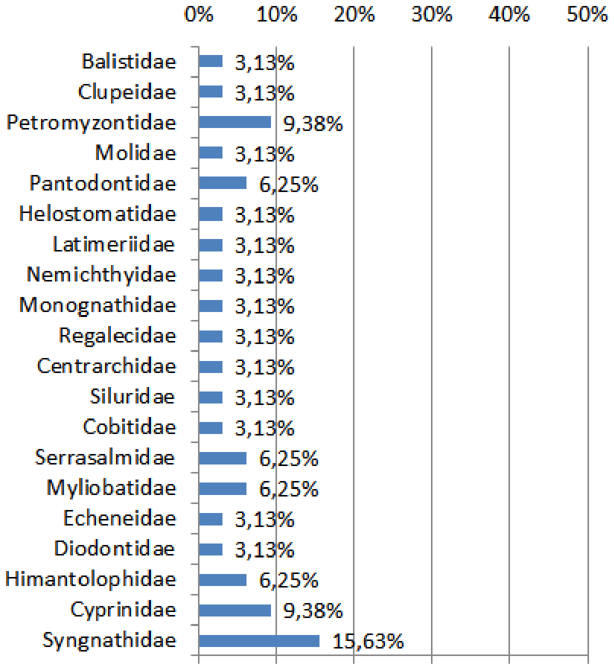

Figure 29. Representativeness of fish families in *Pokémon*.

ALMOST A BIOLOGICAL POCKET-WORLD

Our analysis shows that fish Pokémon are very diverse creatures, both taxonomic and ecologically, despite being a small group within the Pokémon universe (with 801 "species").

The fish Pokémon are represented by several orders, families and genera of real fishes and, as previously stated, this is actually a relevant sampling of the ichthyological diversity of our planet. The marine Pokémon described here are inhabit from abyssal zones to coastal regions, including reefs. The creative process of the fish monsters in the game must have included a fair share of research on real animals.

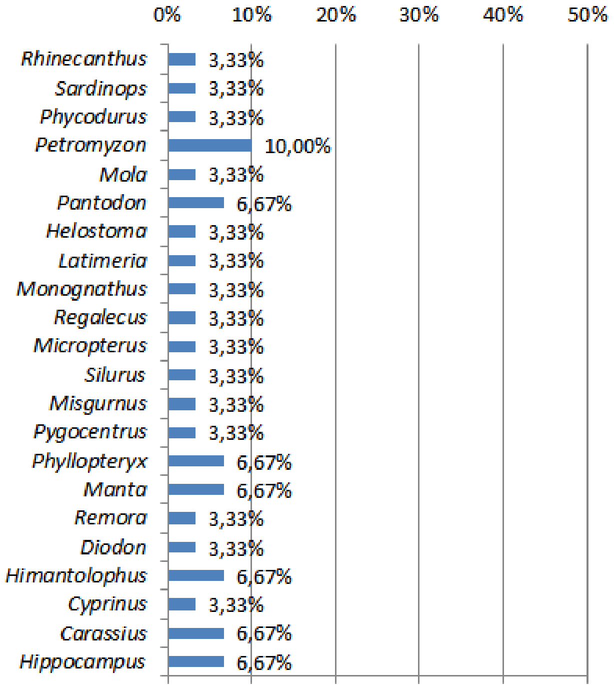

Figure 30. Representativeness of fish genera in *Pokémon*.

The Hoenn region, which has the largest playable surface and includes areas with "too much water", is also the region with the highest number of fish Pokémon. Furthermore, the majority of these Pokémon live in the marine environment and belongs to the Osteichthyes class, as is observed for real fishes (Nelson et al., 2016; Eschmeyer et al., 2016). However, it is also important to underline that marine fishes are those with the more attractive colors and shapes and, therefore, higher popular appeal, which is vital for a game based in charismatic monsters (Darwall et al., 2011; McClenachan, 2012; Dulvy et al., 2014).

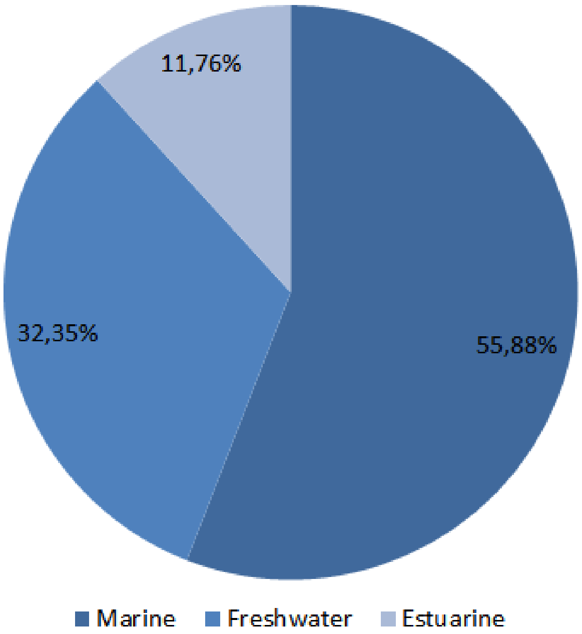

Figure 31. Environments inhabited by the fish Pokémon.

In the present work, the analogy between fish Pokémon and real species allowed a descriptive study of the "Pokéfauna" in a similar manner in which actual faunal surveys are presented. These surveys are an important tool for understanding the structure of communities and to evaluate the conservation status of natural environments (Buckup et al., 2014). It is noteworthy that the association of the monsters with real fishes was only possible because Pokémon have several morphological, ecological and ethological traits that were based on real species.

Pokémon is a successful franchise and many of its staple monsters are already part of the popular imaginary. The creation of the pocket monsters was not done in a random manner; they were mostly inspired by real organisms, particularly animals, and often have specific biological traits taken from their source of inspiration. Thus, analogies between Pokémon and our natural world, such as the ones performed here, open a range of possibilities for science outreach.

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ABOUT THE AUTHORS

Augusto Mendes began his journey as a Pokémon trainer in his childhood, when his parents gave him a green Game Boy Color with *Pokémon Red* for Christmas. Currently, he is a master's degree student in the Program of Marine Biology and Coastal Environments of UFF, where he works with zooarchaeology of fishes and education.

Felipe Guimarães is in love with Pokémon (since he first watched the TV series) and the natural world. He graduated in Biology from the UERJ, where he worked with taxonomy and ecology of fishes. He also works with popularization of science and environmental education.

Clara Eirado-Silva, when she was eight years old, told her parents she would study sharks. She has always been passionate about art too and draw since her childhood. Currently, she holds a "Junior Science" scholarship, working on fishing ecology with emphasis on reproductive biology. In her free time, she draws her much loved fishes.

Although Pokémon is not exactly Dr. **Edson Silva**'s cup of tea, he watched all movies with his daughter, who's crazy about the little monsters. As fate would have it, his work on population genetics of marine organisms attracted a master's student (A.B.M.) who's an equally crazy pokéfan. May Arceus not spare him from the monsters!

Journal of Geek Studies

ISSN 2359-3024

Impossible possibilities: a super-runner's speed limit

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Super heroes: their attitudes and honor codes make them heroes; their extraordinary abilities make them super. Such abilities may be believable, based on mundane training and technology but, more often than not, they surpass not only human limits, but the borders of physics as well. For example: moving faster than light, ignoring laws of mass and energy conservation, manipulating matter and energy with a thought, etc.

Many questions come to mind when thinking about supers, one in particular: what are the limits of what is physically possible? When a character receives an extraordinary power, how does it interact with an ordinary world? In this study, I'd like to invite the reader to explore the boundaries of one of the most classical archetypes: the super-runner.

INITIAL SCOPE

As I don't want to cause indignation to any fan while talking about limitations of his or her favorite character – such as Flash (Fig. 1), Quicksilver (Fig. 2) and other famous speedsters – let's adopt an unknown super hero, henceforth called Captain Run (any similarity with characters from any multiverse is just a coincidence), to whom I shall give increasing powers, testing how fast a super-runner can go.

Figure 1. Different versions of DC's The Flash. Image extracted from Wikimedia Commons; artwork for the cover of Flash (vol. 2, #208; DC Comics, May 2004), art by M. Turner & P. Steigerwald.

Some may find it weird to talk about "super-runner" instead of using the term "speedster".

The reason is that I will limit our study to powers that are (roughly) related to running. So, I will avoid time-stopping, n-th dimension jumping, space compression and any other "physics' law-suppressing" powers, otherwise there would be little physics left to study. That being said, from now on, I may use both terms speedster and super-runner, but Captain Run's powers will be limited to running abilities.

Figure 2. Marvel's Quicksilver. Image extracted from Wikimedia Commons; panel from Avengers (vol. 3, #38; Marvel Comics, March 2001), art by A. Davis.

Let's start slow. What if the Captain had human speed? The top speed registered for a running human was achieved by Usain Bolt in the 100 meters race at Berlin 2009 (Fig. 3; German Athletics Federation, 2009), when he travelled from the 60m to the 80m line in 1.61 seconds. This means a speed of 12.4 m/s or 44.6 km/h.

Figure 3. Usain Bolt (second from right to left) winning the 100 m in Berlin 2009. Image extracted from Wikimedia Commons; E. van Leeuwen (2009).

This speed is comparable to that of cars in urban areas, a remarkable feat for a biped made of flesh and bone. But if our goal is to go beyond real humans, how about the limits of the animal kingdom? The fastest known land runner is the cheetah (*Acinonyx jubatus*) who, when pursuing their prey, can run at up to 100 km/h for short periods of time (Carwardine, 2008). That clearly served as inspiration for the Thundercat speedster Cheetara (Fig. 4).

Figure 4. Cheetara, from *Thundercats*. Image extracted from www.thundercatsfans.org; screen capture from the animated series.

Better, but not enough. Our hero is still stuck to biological limitations: muscle contraction rate, step mechanics, motor coordination, metabolism, fatigue, etc. Alright, it's time to go super!

Let's give Captain Run the following powers: (1) the ability to move body parts as fast as needed, no longer constrained by physiology; (2) reflexes and brain functions fast enough to coordinate such movements; (3) the capacity to accumulate enough energy and use it with enough potency to enable this speed; and (4) sufficient invulnerability to avoid harm from the usage of his powers within normal circumstances. Captain's uniform is super resistant and includes special googles that repel any particles, never getting blurry.

With all that, what limits our hero? Basically, friction.

FRICTION: PUSHING AND BLOCKING

When someone stands on a horizontal surface, their body is pulled towards the planet's center due to gravitational attraction, aka weight force. Their feet touch the ground and apply a force on it, whose reaction is applied by the ground on the feet and balances the weight force, so that the body remains static. This contact force is perpendicular to the surface, and is usually called normal force (F_N).

When someone tries to run, their feet (or their footwear's sole) perform a movement whose tendency would be to slide backward. If there is too little friction, as on an oil puddle, the runner slips. However, if the interaction between foot and ground is sufficiently strong to resist slipping, the foot will push the ground backward while the ground will push the foot forward, propelling the runner forward (Fig. 5). In this case we have what is called static friction: a property of two surfaces to resist sliding so that there is no relative movement.

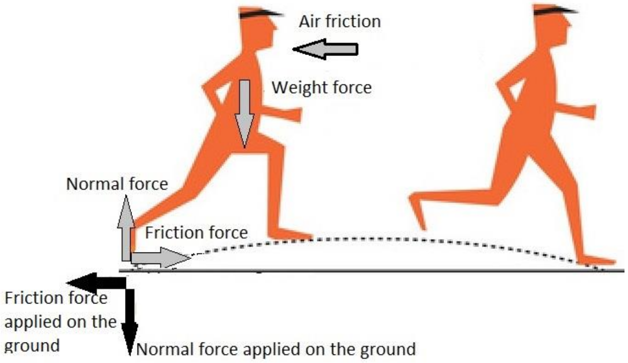

Figure 5. A runner's force diagram. Image modified from *Forces in Running* (http://forces-in-running.weebly.com/).

The static friction has a limit that depends on: (1) the normal force between the surfaces – that is, how much they compress each other; and (2) the nature of the touching surfaces, meaning the materials they are made of, if there are particles (dust) or fluid (oil, water) between them, and if the surfaces are smooth or rough. In general, one can use the expression:

$$F_{friction} \leq \mu \cdot F_N$$

where $F_{friction}$ is the friction force, F_N is the normal force, and μ is the friction coefficient, an empirical dimensionless number found through many experiments with different materials and conditions. If the Captain's foot tries to apply a horizontal force greater than $\mu \cdot F_N$ onto the ground, his foot slips; therefore, $\mu \cdot F_N$ is the maximum force he can use to impel himself forward.

The analysis gets more complicated when we consider the human step mechanics, which involves vertical displacement, the feet and legs changing position, forces changing directions at every moment, among other complications. In order to focus on the overall external physics, I will use a radical simplification, adopting average values and ignoring most of the step mechanics.

In this simplified model, the normal force will be considered constant, and a horizontal trajectory will be chosen so that there is no vertical displacement. Therefore, in general conditions, the normal force's magnitude will be equal to the weight force (we will see later on that this can change under certain circumstances).

Also, the friction coefficient μ will be considered constant and adopted as 1, which represents boots made of tire rubber on dry asphalt from a regular street (lower values represent more slippery surfaces; higher values are found in more adherent interactions, like rubber shoes on rubber floor; for more examples, see The Engineering ToolBox, 2017). Simulating a wide range of values for a varying μ as the Captain runs would consume too much time and effort while adopting a scenario as fictional as any. If we have to pick a track, let's stick to the basics.

With these premises, the expression for friction force says that $F_{friction} \leq$ weight. By Newton's second law, one may conclude that Captain Run could achieve an acceleration equal to the gravitational acceleration, about 9.8 m/s². Does this mean he can speed up at 9.8 m/s², as if he were "free falling forward" indefinitely?

Not really. And that is because we still haven't talked about the other "friction": the air resistance. The interaction of a moving body and the fluid it is immersed in depends on the body's size, geometry and position, and increases with the relative speed between them, generating a force opposed to the movement. This force may be called drag, air friction or air resistance. A free falling body's acceleration decreases as the drag increases, up to the point when drag = weight. At such a point, it is said that the body has hit its terminal velocity.

For a skydiver with open arms and legs and parachute still closed (Fig. 6; this is the closest to a person running with an erect posture that can be found in literature), the terminal velocity is of about 60 m/s or 216 km/h (Nave, 2012). This is fast for sure, but not as extraordinary as we wanted; after all, there are land vehicles which can go faster than that. So, how can we go faster if, at this point, the air resistance equals the maximum propelling force we can achieve? Let's take a deeper look.

Figure 6. Depiction of a freefalling skydiver. Image extracted from *Buzzle* (www.buzzle.com).

The drag force for a turbulent flow (in short, at high relative speeds) around a body is given by the expression:

$$F_{drag} = \frac{1}{2} \cdot \rho \cdot C_{drag} \cdot A \cdot V^2$$

where F_{drag} is the drag force; ρ is the fluid's density; A is the reference area, which can be the total area in contact with the fluid, or the frontal area (the "shadow" the body creates in the fluid's flow lines); C_{drag} is the drag coefficient, a dimensionless number obtained by experiments (it depends on the area A considered and the body's geometry and stance, and the fluid's viscosity); and V is the relative speed between body and fluid.

The terminal velocity is reached when V is so high that the drag equals the propelling force, which I estimated as being equal to Captain's weight (if he tries to impose more force, his feet will slip on the ground without speeding up), so:

$$F_{friction.max} = F_{drag} \Rightarrow m \cdot g = \frac{1}{2} \cdot \rho \cdot C_{drag} \cdot A \cdot V_{max}^2 \Rightarrow \boxed{V_{max} = \sqrt{\frac{2 \cdot m \cdot g}{\rho \cdot C_{drag} \cdot A}}}$$

Considering this equation, which powers or tricks could the Captain use to run faster? He could change his stance to reduce the drag, much like bikers leaning and even lying on their motorcycles in order to generate less drag (this may explain why some authors depict their characters running with their torso in a horizontal stance). Still, the limit wouldn't be "super" higher.

The Captain could try some technology or obtain a new power to shrink (reducing the $A \cdot C_{drag}$ term) while keeping the same mass, or increase his mass while keeping his shape (with a suit made of super heavy materials, for example). However, he would then have another problem because, at some point, his weight would be concentrated in such a reduced area, that he would possibly pierce the floor and leave a trail of destruction in his path.

By the way, collateral damage would be an issue if Captain Run were to get close to another famous limit: the sound barrier (Fig. 7). The sound travels at different speeds depending on characteristics of the medium transmitting it; in air at 20°C and at sea level, the speed of sound is 343 m/s or 1,236 km/h. When a body travels in a fluid with a speed equal to or higher than the speed of sound, it provokes shockwaves that release a great amount of sonic energy, a phenomenon called "sonic boom".

This sonic boom, when caused by airships flying kilometers above the ground, can shake some houses' windows. So how much damage would Captain's sonic boom cause if generated in the middle of the street? In a best case scenario, bystanders would suffer temporary deafness and glass objects would be shattered, resulting in a high chance of getting sued (Gilliland, 2014).

Figure 7. Sonic boom forming as an aircraft breaks the sound barrier. Image extracted from *Shutterstock* (www.shutterstock.com).

Well, as destroying the pavement and bursting eardrums are usually villains' jobs, let's avoid that by giving our hero another (quite unrealistic) power: the capacity of not interacting with the air. Let's assume that he can generate a field around his body that distorts physics so he doesn't generate turbulence, drag or sonic booms.

With such not-very-realistic science, Captain can finally reach the speed of light, right? Not so fast. That is because, until now, I have been applying an implicit simplification: the path through which the Captain runs was considered a straight line. Even though this is an adequate model when dealing with "everyday" velocities, we must remember that Earth's surface is not flat, but round, so one actually performs a curved trajectory when running straight forward. This makes a difference when we start to go superfast.

RUNNING AROUND THE GLOBE: THE GRAVITY OF THE PROBLEM

In order to follow a curve, a body needs a resulting force with a component perpendicular to the speed so that it alters the speed's direction. This force is called centripetal force, given by:

$$F_{cent} = \frac{m \cdot V^2}{R}$$

where F_{cent} is the centripetal force needed for a body with mass m moving at a speed of magnitude V to follow a curve with a radius R (Fig. 8).

In most cases, as Earth's radius is quite big and V is not too high, F_{cent} is low enough so one can ignore it without distorting the results, but as V increases, that's not the case anymore.

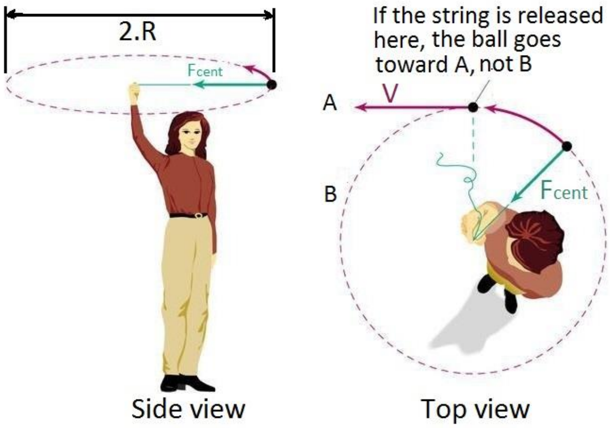

Figure 8. Centripetal force acting on a ball attached to a string being swung in circles. Image modified from *Boys and Girls Science and Tech Club* (https://bgsctechclub.wordpress.com/)

When I estimated the propelling force as being equal to the weight force, I assumed that F_N = weight, so the resulting force in the vertical direction would be null. However, as we make a curve around the Earth, we need a resulting force equal to the centripetal force, so that the difference between the weight and normal force keep the body from leaving the planet's surface.

As we are talking about planetary scale, let's take a look at the expression for gravitational attraction, because, in reality, using $g = 9.8 \text{ m/s}^2$ was another implicit simplification. According to Newton's gravitational law:

$$F_g = \frac{G \cdot M \cdot m}{R^2}$$

where F_g is the gravitational force between two bodies; G is the universal gravitational constant, which was obtained through experiments to correlate F_g and the other physical quantities; M is the mass from one of the bodies, in our case, Earth's; m is the other body's mass, in our case, Captain's; R is the distance between the two bodies' centers of mass.

I will assume Earth's shape to be a sphere (which is not exactly true, but this is not the worst approximation I've done so far) and that Captain's height is negligible in face of Earth's medium radius, so that R = 6,371 km.

When we study a problem in planetary scale, another issue arises: the Coriolis force, a fictitious force that appears when a body tries to move on a spinning frame of reference (such as the Earth) and the former's speed is not parallel to the latter's axis of rotation (Persson, 2005). Earth spins with an angular speed of 2π/day around an axis that passes through the planet from North to South. If the Captain stands still at the equatorial line, he performs a circular trajectory with a radius of 6,371 km at a speed of (2π/day) times 6,371 km. Standing at the poles, he just spins around himself, with zero speed. At each latitude between these extremes, he will have a different linear speed caused by rotation.

Now, let's assume he is running at super speed and steps on the North Pole. At first, he would have a speed towards south only. If he goes on, however, he will arrive at points that rotate at a certain speed towards east, so two things may happen: either he accompanies Earth's rotation, which means he needs an additional force to impel him to the east (it would "consume" part of the friction); or he keeps running south, and appears to be sliding west in relation to the ground.

Adding Coriolis force to the analysis would be way too complicated, but there is a way (literally) around this: if the Captain runs only over the equatorial line, the ground would always be at the same speed (ignoring mountains and other geographic features). In this case, the Coriolis force would no longer affect our hero's speed direction to the sides (it becomes 100% vertical, like weight and centripetal forces), and we can build a simpler model using his speed referenced by Earth's center by applying a correction to speed due to rotation.

So, back to the study of forces in the vertical direction, using V with reference to Earth's center, we have:

$$F_g - F_N = F_{cent} \Rightarrow F_N = \frac{G \cdot M \cdot m}{R^2} - \frac{m \cdot V^2}{R}$$

Applying Newton's second law, I can calculate Captain's acceleration as:

$$F_{friction} = m \cdot a \Rightarrow a = \mu\left(\frac{G \cdot M}{R^2} - \frac{V^2}{R}\right)$$

This means that, as the speed increases, the acceleration decreases. As I assumed a constant radius R, G is constant by definition, and Earth's mass doesn't present significant change in a day, I can calculate that our hero's top speed would be:

$$a = 0 \Rightarrow V_{orb} = \sqrt{\frac{G \cdot M}{R}} = 7{,}909.68\,m/s$$

When achieving such a speed, any person would enter an orbit close to the ground. At this speed, the gravitational force keeps the body in a circular trajectory, keeping it from escaping into space, but not allowing enough interaction with the ground to have any normal force or friction force. Even if the Captain wore an extremely massive armor or super-adherent boots to increase his traction, when he reached 7,909 m/s relative to Earth's center, there would be no more contact with the floor for him to accelerate any further.

Basically, the Captain would be floating a few centimeters above the ground, without touching it with his feet, and thus limiting his running speed.

If I consider that any point at the equatorial line moves at 465 m/s relative to Earth's center, due to the planet's rotation, and that the Captain can move at up to around 7,900 m/s, when seen by a reference on the ground he can run at 8,365 m/s when moving towards west, or 7,435 m/s when moving towards east. Therefore, at max speed, he could go around the planet in about 79 minutes and 40 seconds. Not instantaneous, but not bad either.

Still, as we have seen, his acceleration drops as his speed increases. Therefore, the faster he is, the harder it is for him to get even faster. With that said, how long would Captain Run take to reach top speed?

ACCELERATION: HOW FAST ONE GETS FASTER

Acceleration is the rate at which speed varies in time. As we have seen, a super runner has limitations to his acceleration, so he can't reach the speed of sound in the blink of an eye. That, by the way, is one of the most common stunts performed by speedsters that contradicts the laws of physics, demanding explanations like time distortion.

For example, in Disney-Pixar's *The Incredibles*, the young speedster Dash (Fig. 9) is presented as a boy who can run superfast, without mentioning time-space manipulation abilities. He doesn't even ignore air resistance, for his hair is clearly dragged when he is running. Yet, Dash performs an impossible prank where he runs across a room full of people without anybody noticing, not even with the aid of a camera.

Figure 9. Dash, from *The Incredibles*. Image extracted from *The Disney Wiki* (http://disney.wikia.com).

In a rough estimation, he runs about 5 m from his seat to the front of the room, and 5 m back to his seat, all in the time between two frames captured by a hidden video camera. Even the cameras from the silent films period took images at a minimum rate of 16 frames per second (Wikipedia, 2017a), which means he had 0.0625 seconds to do it, at best. So, a minimum average speed of (2 x 5 m) / (0.0625 seconds) = 160 m/s was needed. What is the problem with that?

First of all, he was wearing common clothes at the time and not his special anti-air friction suit, so he would at least provoke a sudden blow of wind and a lot of noise, startling everybody in the room.

Second, if he had 0.0625 seconds to do all the work, he had even less time to accelerate and decelerate. When he got to the front of the room and turned back, he had to reverse accelerate at more than (2 x 160 m/s) / (0.0625 s) = 5,120 m/s², or 522 times the gravity acceleration. There is no way his regular shoes would stand so much friction with the ground without some damage or skidding occurring. Also, if he tried some maneuver like a wall-kick, he would probably poke a hole through the wall, not to mention the noise caused by the impact. Incredible indeed.

Right, you can't run with infinite acceleration without destroying some objects in the way. Isn't there another way? One "possible" solution to the acceleration limitation is to use jet propulsion: by discharging a stream of gas at high-speed backwards, one is propelled forward. One example is the hero in training Tenya Iida, from the manga/anime *Boku no Hero Academia* (Fig. 10), who has some sort of bio-organic engines in his calves. The story has yet to explain (if it ever will) how much thrust he gets from the expelled gas and how much comes from superfast leg motion. How he coordinates the propulsion with the variation of his legs' positions while running is another mystery.

Figure 10. Tenya Iida from *Boku no Hero Academia*, using his powers. Image extracted from *Boku no Hero Academia Wiki* (http://bokunoheroacademia.wikia.com), excerpt from the manga.

Anyway, this can help at some level, but again there is the collateral damage issue: once the gas leaves the hero's body or equipment, it will interact with the environment, possibly causing sonic booms or pushing unaware bystanders away, depending on the acceleration he is trying to achieve or the speed he is running at.

With that in mind, let's go back to Captain Run dealing with his limited acceleration. As we have seen, the maximum acceleration he can achieve depends on his interaction with the ground, the gravity and the centripetal force needed to keep him on Earth's surface. This can be expressed through the equation:

$$a = \mu\left(\frac{G \cdot M}{R^2} - \frac{V^2}{R}\right)$$

With all the constants known, the only variables left are the acceleration and the speed. Through numerical calculations I can estimate how these two quantities would vary if the Captain tried to achieve his maximum speed at the maximum available acceleration (Table 1).

Starting his movement standing at the equatorial line (rotating east at 465 m/s relative to Earth's center, due to planetary rotation), running towards west, he would take 35 seconds and go through 6 km to reach the speed of sound relative to the ground.

Table 1. Variation in speed and acceleration as Captain Run speeds up.

Time spent [s]	Speed relative to Earth's center [m/s]	Acceleration [m/s²]	Distance run through [m]
0	-465	9.79	0
35	-122	9.8	5994.4
47.4	-0.07	9.82	11000
311	2501	8.84	469000
757	5593	4.91	2550000
1108	6850	2.46	4920000
1512	7504	0.982	8030000
2458	7870	0.0982	15800000
3380	7906	0.00987	23500000
4050	7909	0.00175	29100000
5350	7909.66	0.0000612	40000000

He would take 47.4 seconds and 11 km to reach 465 m/s, or 0 m/s relative to Earth's center. After 311 seconds and 469 km run, his speed would be 2,501 m/s relative to Earth's center and his acceleration would have dropped by 10%.

To illustrate how his speed and acceleration evolve, let's use these quantities in relative forms:

$$V^* = \frac{V + V_e}{V_{orb}} \quad ; \quad a^* = \frac{a}{a_0}$$

where V* is the relative speed (reference on the ground), a* is the relative acceleration, V_e is the equatorial line rotational speed and a_0 is the maximum possible acceleration, when V=0. Plotting this on a graph in logarithmic time scale, we have Figure 11.

One can see from Table 1 that, after 2,458 seconds (about 41 minutes), 16,000 km run (equivalent to almost 10 time zones), our hero would reach 99% of his top speed, and would have only 1% of his maximum acceleration still available. There is no highway long enough for this, but… moving on.

After 4,050 seconds, he would reach 99.99% of his max speed V_{orb}. Any irregularity on the ground, like a speedbump, might be used as a steppingstone to get one last push and hit the zero height orbit speed.

According to these estimations, he would take 5,353 seconds (about 89 minutes) to finish his trajectory around the planet and, from then on, would orbit close to the ground at 7.9 km/s (establishing an orbital period of 5,060 seconds or about 84.3 minutes). That is, if he didn't collide with some object in his path, like a tree, building, mountain, etc. Given Earth's topography, it doesn't sound very likely.

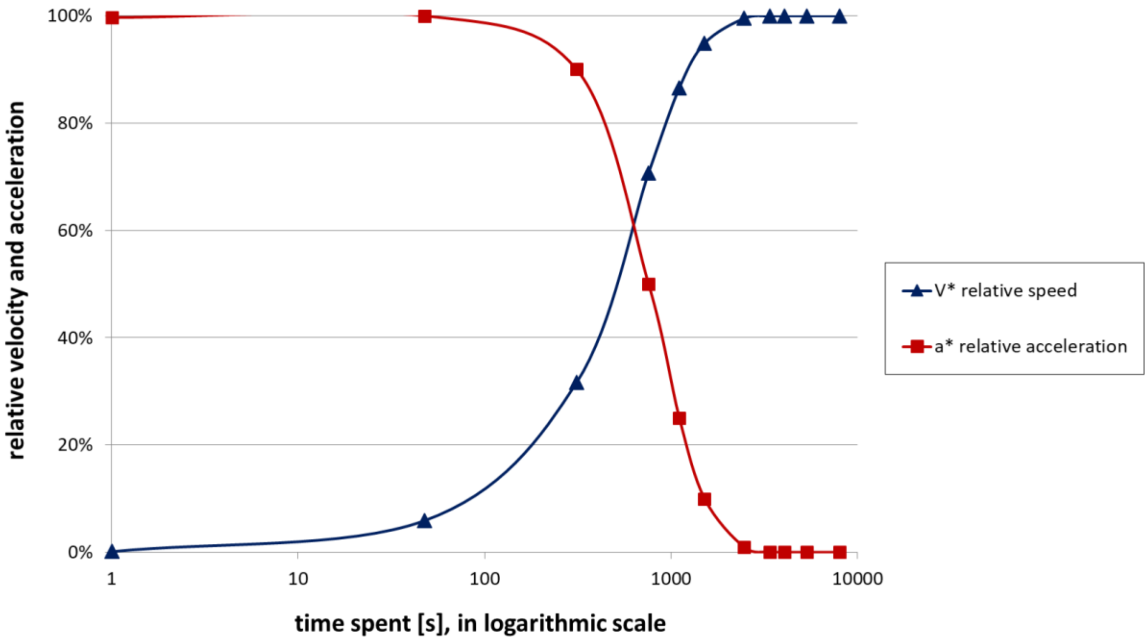

Figure 11. Variation in relative speed and acceleration as Captain Run speeds up.

COLLISION COURSE

Another problem thus becomes evident: how will the Captain dodge obstacles? As we have seen, when one's speed increases, the interaction with the ground decreases. This means his acceleration is more limited, not only to make him go faster, but also to hit the brakes, or even to perform a curve and avoid collision.

Then, another question comes to mind: what is the speed limit if he intends to dodge from random obstacles? Sure, it depends on the nature and size of such an obstacle, but I can try to estimate it.

Let's assume Captain is running in an open field, when he sees a small town. He decides entering the town is not a good idea, since he might hit innocent citizens, so he prefers to contour it.

The distance to the horizon line depends on a combination between the planet's curvature and the height of the observer's eyes above the ground (the altitude as well, but to simplify everything, let's consider he is at sea level). Some estimates show that, for a point of view with heights varying from 1 to 2 meters above the ground, the distance to the horizon line varies from 3.57 to 5 kilometers (Wikipedia, 2017b).

To use round numbers, let's say the distance to the horizon line is d = 4 km, and the town's shape can be represented by a circle with a radius of r_T = 1 km. When the Captain spots the town's border, he immediately begins to perform a curve of radius r without decelerating, using all the friction force with the ground as centripetal force. Figure 12 shows this problem's geometry.

In this case, the Captain would need to perform a curve of 12 km or less in radius. As we have shown, the faster he goes, the lesser friction force is available, and the harder it is to make a sharp turn.

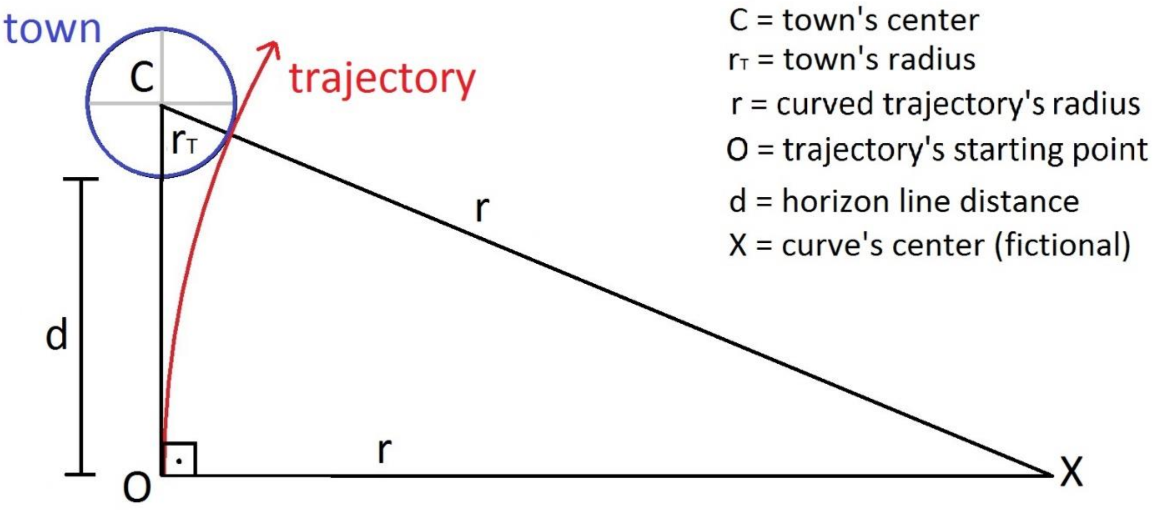

Figure 12. Problem's geometry: a speedster trying not to hit a small town.

If I combine the equations adopted for friction and centripetal force, what we have is:

$$F_{friction} = F_{cent} \Rightarrow \mu \cdot \left(\frac{G \cdot M \cdot m}{R^2} - \frac{m \cdot V^2}{R} \right) = \frac{m \cdot {V_{ground}}^2}{r}$$

In this case, V is the speed considering a reference in Earth's center, while the speed that goes into the centripetal force equation is V_{ground} because the curve is performed on the ground reference.

When the Captain runs towards west (the direction determines the relation between V and V_{ground}), the maximum speed which still allows him to dodge the small town is V_{ground} = 343 m/s (by coincidence, it is close to the speed of sound). Actually, as this speed is low in a planetary scale, the $m \cdot V^2/R$ component of the centrifugal force can be disregarded, and the result is about the same whichever direction the Captain is running.

As I estimated, our super runner runs about 6km to go from zero to 343 m/s. If he attempted to just brake instead of contouring the town, he would need about the same distance to decelerate, which means that he would not be able to stop in time to avoid the collision.

In other words, even if the Captain is theoretically capable of running at up to 7,900 m/s (close to Mach 23), if he goes beyond 343 m/s (about Mach 1), he would take the risk of being unable to deviate from large obstacles such as forests or a small town like the one presented in the example above. This could be even worse depending on visibility conditions or a slippery terrain.

BRACE YOURSELVES: IMPACT IS COMING

I have estimated that super runners should stay under the speed of sound in order to avoid accidental collisions.

Well, what if collision is the goal? For example, if a villain plans to conquer the city with a giant robot which Captain Run must destroy to save the day? How powerful would the impact be?

Assuming Captain is of average weight, let's say 75 kg, and is running at top speed relative to the ground (8,365 m/s), he has a kinetic energy of 2.6 gigajoules (GJ). When measuring the energy of explosions, it is common to use a unit called ton of TNT, which is equal to 4.18 GJ. Therefore, a speedster running at top speed and punching, for example, a giant robot, would hit it with an energy equivalent to 620kg of TNT.

This may sound "weak", but one must remember that all this energy would be applied to a surface the size of a human fist in a mostly unidirectional way, instead of spreading spherically like a bomb explosion usually does. Such destructive potential should not be neglected.

However, such an attack would be quite impractical. According to our estimations, Captain Run would need a 16,000 km long unimpeded straight road and take more than 40 minutes to reach his top speed, giving the villain plenty of time to just move the robot out of the collision course, quickly frustrating our hero's plans.

BEYOND EARTH

So far, I have limited this study to the realm of an earthling super runner: a person on Earth whose powers involve high running speed on the ground, without the ability to distort time, space or gravity.

But wait: what if our hero went to a bigger planet, with higher mass and gravity acceleration, how fast could he go? Well, if one uses a similar math for Jupiter, the biggest planet in our solar system, it has M= 1.898 x 1027 kg and R= 1.42984 x 108 m (NASA, 2017), and the orbital speed at its surface would be 29.8 km/s, almost four times faster than Earth's top speed. There is just one tiny issue: larger planets, such as Jupiter, tend to be gaseous, so it would be a little hard to run on them.

Well, how about giving Captain the power to run over any "surface"? Then, if he finds a big enough celestial body, he would be able to reach the speed of light, yes? Well, probably not.

The speed of light moving through vacuum (it changes depending on the medium it is moving through) is the theoretical limit for displacement rate in our universe, and equals about 300 thousand km/s (10,000 times the estimated maximum speed on Jupiter). The thing is, a celestial body whose surface orbital speed equals the speed of light would have a gravitational field so strong that any photon moving close to it would be unable to move away, getting trapped.

In other words, Captain Run would have to run on a black hole to reach the speed of light. As if resisting the enormous forces wouldn't be tricky enough, he would also have to start his race at a lower speed, in which case his matter would be sucked and disintegrated by the black hole, ending his career in quite a tragic way.

Another way would involve building a planet-sized ring shaped track, and our hero running in its internal surface, like a roller coaster cart in a loop. The faster he goes, the higher the normal force due to centrifugal effects, increasing the friction force available for acceleration.

But this increasing force takes its toll. At some point before hitting the speed of light, the force put on the track would be comparable to those occurring on the surface of a black hole, since Captain Run has an unneglectable mass. At that point, the atomic interactions in either the track's material or Captain's body would not bear the stress anymore, and something would collapse in a very destructive accident.

CONCLUSION

When presenting speedsters' stories, it is easy to make mistakes concerning physics (or simply ignore physics entirely), most of them related to the limits of acceleration.

Considering a super-runner on Earth, if there was a highway completing a loop around the whole planet following the equatorial line, our hero would be able to reach a maximum speed of 7.9 km/s relative to Earth's center (up to 8.4 km/s relative to the ground, depending on the direction he is running). From then on, due to gravitational and centrifugal effects, he would be unable to accelerate any further. Even with quite unrealistic capabilities, such as ignoring atmospheric interactions and biophysical limitations, our hero can barely get to 0.01% of a photon's speed.

Still considering Earth's limitations, the super-runner could punch an immobile target with energy equivalent to 620 kg of TNT, supposing he had enough time and space to prepare his attack and his body being able to withstand the impact.

However, for safety's sake, it would be inappropriate to go beyond 343 m/s, otherwise accidental collisions might cause undesirable damage to people, property, fauna and/or flora.

In order to reach the dream of light speed, one could try to use more massive celestial bodies, or build a planet-sized ring track. Still, unless one had superpowers and materials able to withstand the forces found on a black hole's surface, disintegration would come long before the speed of light.

In conclusion, unless we include powers to further distort time-space or other physical laws around one's body, even without considering relativistic effects, we can say it is impossible for a hero to run at the speed of light.

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ABOUT THE AUTHOR

Gabriel understands that, if physics were to be taken too seriously, and every interaction had to be carefully calculated, there would be a terrible shortage of stories about supers available to be enjoyed. Nevertheless, he will continue in his journey to unveil possible and impossible explanations for the mysteries of the multiverse based on the science of our boring real world and, maybe one day, find a way to become an actual supervill… hero. Superhero. Of course.

Journal of Geek Studies Vol. 4(1). 2017.