Playing with Science: games as a medium of science communication

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Abstract:

By metrics, such as average play hours and money spent (as measured per capita or market gross volume), gaming is at the forefront of cultural content consumption; being the most popular form of entertainment in the developed world. While the most common association with gaming would be related to digital gaming, traditional games, such as tabletop roleplaying games and boardgames, are undergoing their own renaissance. All the while, classic traditional games like chess or classic deck card games remain popular. For science communicators, it is important to acknowledge games as effective learning and communication tools.

To date, there is no broad-perspective evaluation of the gaming medium published for science communicators. There exist singular studies dealing mostly with digital games, but their particularities have not been explored comparatively. This chapter defines a game; outlines a brief history of games, the parameters, and genres of gaming, and discusses a selection of games that act as science learning and communication tools. Furthermore, our own experience designing "*Belly Rumble: a microbiota board game*" will contextualise the use of tabletop board games as a biomedical visualisation learning tool.

Introduction:

To have any discussion on the potential applications of gaming for science communication, it is important to establish what a game is. There exist many published works analysing the phenomenon of gaming through different methodological lenses; however, they often bemoan the lack of commonly accepted and/or clearly delineated taxonomy of games (Ruggill & McAllister, 2011; Shubik, 1983).

Definition of a game:

Huizinga (1938) outlines many qualities of play rather than gaming that include engrossment with the activity (both that of the spectators and the participants), disinvolvement from the realities of daily life, participants experiencing ‘fun’, and repetitiveness; play being able to be completed and then performed again in its designed form somewhere and sometime else. Other traits include time constraints and specific space in which the play takes part, ritualised rules, layout of the game play and lastly the community-building effect of play activity. Huizinga (1938) also extends the principles of play to include diverse phenomena such as performance art, adjudication, warfare and other areas of human experience (Tanghe, 2016). This is indicative of how the experience of play is integral to the human condition and, by extension, so is that of gaming.

Huizinga’s approach is philosophical and reflective, in contrast to more modern, academic models. For example, in 2010, Arnetta established a set of directives to recognise a ‘game’. There are commonalities between the two approaches, and these are listed in Table 1.

ANALOGOUS CONCEPTS BETWEEN TWO THEORIES OF GAMING	
Huizinga (1938)	**Annetta (2010)**
Engrossment	Immersion
Time, space, and set-up specificity	Identity
Disinvolvement with reality	Immersion
Repetitiveness and replicability	Interactivity
Community building	Identity

Table 1: Analogous concepts between the Huiznga's and Arnetta's Frameworks

Furthermore, there is a great deal of nuance when considering what passes for a game. One could define a game as any activity that involves one or more players and has defined rules of victory that can be resolved by the end of said activity's sequence. Such definition would stretch to board games, most videogames, card games and sports, but would exclude roleplaying games, freeform play and some videogames that might include cinematic choice-based stories (Arrambide Figueora, 2022). Using term 'rules of play' as opposed to 'rules of victory' helps accommodate said exceptions, but further opens the definition to more diverse aspects of daily life.

Traditionally, sports including football and the Olympic disciplines all meet the aforementioned criteria, but there exists a pervasive cultural perception of sports as a separate phenomenon; it seems to be implicitly understood that playing football is participating in a sport, however playing chess is considered gaming. There are arguments to be made on both sides and Kobiela (2018) argue for the inclusion of games in sports under the term 'mental sports'. The opposite argument could be made by naming football an 'athletic game'. The boundaries become even more unclear when one considers the phenomenon of E-sports. In this case, competitive video gaming is considered by some a veritable sporting activity (Jenny et al., 2017). It is a controversial space and public discourse presents arguments for both the inclusion and exclusion of e-sports from the purview of sportsmanship proper. Given, that E-sports garner remarkable spectatorship and funding, perhaps the cultural perceptual difference between the 'games' and 'sports' may be predicated upon profitability and public engagement (Jenny *et al.*, 2017). Does a game become instead an 'E-sport' after generating a large and profitable enough competitive scene?

The common quality of activities commonly considered 'sports' is physical exertion. To focus the scope of this chapter, the integral element of physical exertion has been elected as an exclusion criterion, an approach shared by others, including Parry (2019). None of the games considered within this chapter necessarily involve physical exertion. Even though it can be present as an element of Live Action Role Playing (LARP) games or megagames, it is rarely a requirement of playing them and does not significantly affect their resolution. However, some people choose to include simulated physical activity in their games, for example, playing virtual sports (e.g., FIFA and Madden) while remaining sedentary (Jenny *et al.*, 2017).

Considering the criteria mentioned above and informed by Arnetta's (2010) model, for the purpose of this chapter a 'game' will be defined as having these characteristics:

1. Feeling the activity can be successfully completed.
2. The player can concentrate fully on the activity.
3. The activity has clear goals.
4. The activity provides fast feedback.
5. The player is deeply involved in the activity.
6. A sense of control over the actions is necessary to perform the activity.
7. Self-awareness disappears during flow.
8. There is an altered sense of time.

Brief history of gaming:

Playing games is arguably an activity integral to the human experience. In archaeological sites spread across the continents and cultures, one often discovers dice, gameboards and other gaming paraphernalia (see Figures 1 and 2). One of the oldest games with a traceable history is Ancient Indian game of Chaturanga – a known direct descendant of chess, played possibly as far back as 3000 B.C. and no later than 6th century A.D. This game has been argued to be an early example of a boardgame, a wargame and a roleplaying game (Ewalt, 2013).

Figure 1: Ancient Egyptian icosaahedral dice. The purpose of it is unclear and is theorised to be either used for divination practices or gaming. Nate the structural similarity to a later, modern example (Open Access).

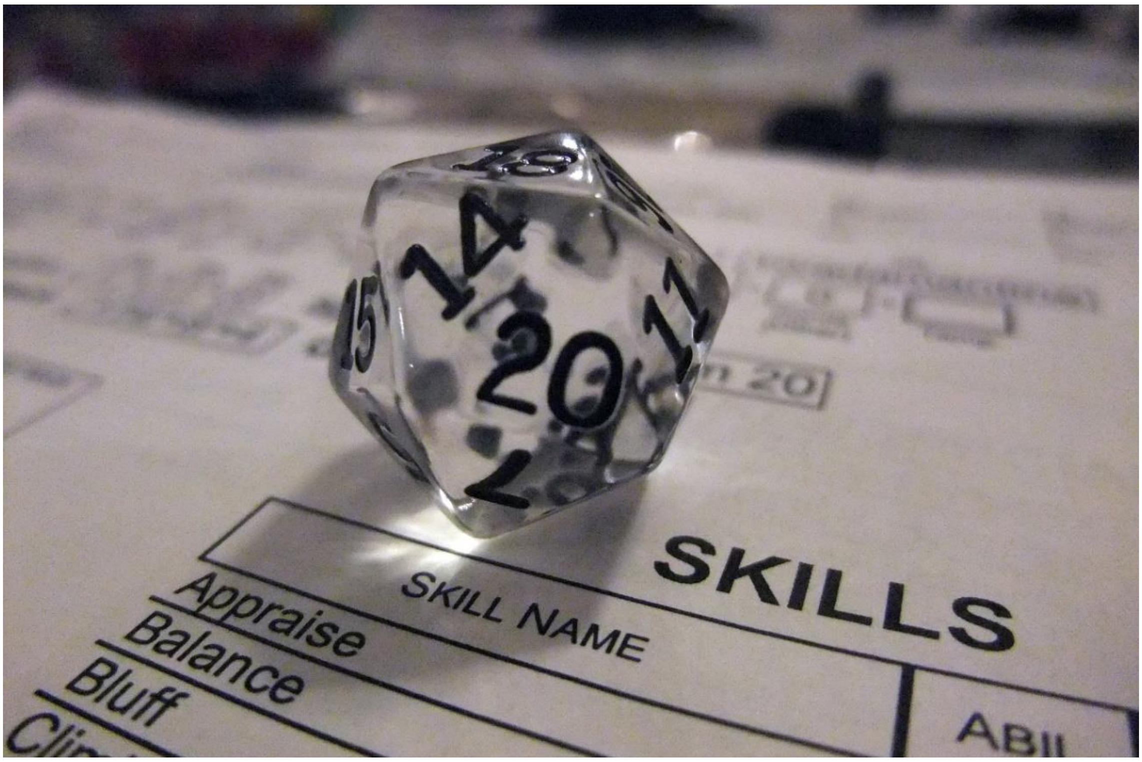

Figure 2: Modern retail available icosahedral (d20) dice included for comparison. Commonly used in Roleplaying games like Dungeons and Dragons. (Creative Commons)

In his landmark publication, *Homo Ludens* (1938), Johan Huizinga argues that play participation is as intrinsic to the human experience as reasoning, speech, or toolmaking. He also draws a compelling case for the universality of play, citing dogs engaging in play-fights with the appreciation of boundaries, conventions, and rules (e.g. pretending to attack the throat but not biting hard). In fact, many species of mammals and birds engage in forms of play, analogous to that observed in humans (Tanghe, 2016; Pellis and Pellis, 2017; Gray, 2019). An idea presents itself, that perhaps play behaviour is an evolutionary adaptation that lets the animal boundary-test and simulate important, yet dangerous activity in a safe, inconsequential environment (Gray, 2019).

Arguably, games that take place in theatre of the mind such as roleplaying games, may be the oldest form of organised human gaming. At their very basic core experience they require an ability to tell a story; an arbiter (being a subjective person) or impersonal game mechanics or a mix of both, and to resolve any conflicts within the story (Ewalt, 2013). Analysis of ancient Greek accounts of gaming by writers such as Herodotus or Plato (Ariel, 1940), not only describes many types of board games recognisable to the modern audience including racing dice games similar to chutes and ladders, and war games, but also mentions the prevalence of such games amongst geographically distant cultures such as the Celts.

Spanish conquistadors found the Mesoamerican native peoples playing a boardgame of ‘Patolli’ – a game of strategy and chance played over material stakes (Erasmus, 1950). The game’s description and layout are functionally near identical to a known Indian game of ‘Pachisi’ (Fig. 3) dating back to circa 1100-800 B.C. (Finkel, 2004). Given the historical migrations of populations, the game has either predated the prehistoric land migration to North America or was developed independently in a near-identical form. A similar game is marketed contemporarily in Western markets as ‘Ludo’ and was introduced by British sailors travelling between Britain and India (Bell, Richard, 1979). This point serves to illustrate the cultural pervasiveness and longevity of gaming.

Figure 3: An example board and pieces of the game of Pachisi. Note the structural and gameplay similarities between this game and both the Pre-Contact Mesoamerican Patolli and the modern marketed game of Ludo (Creative Commons).

An important historical employment of 'serious gaming', which is gaming for the explicit purpose beyond enjoyment (Giasolli et al., 2006), are war games. Going back to the 17th century there are confirmed historical instances of military forces using game pieces and board to simulate combat encounters in order to inform the future strategy (Glick and Charters, 1983). Given, that both the evidence of warfare and tabletop gaming predate that, and the relatively low technological requirement for producing such simulations, such games could have existed for far longer. Moreover, if one considers any sort of war training scenarios involving real world drills and simulated combat that are structurally reminiscent of LARP or megagames, they can be observed as games (Eng, 2020).

A major development in modern gaming is the introduction of digital games, with the text based 'The Oregon Trail' being recognised as the first commercially available digital game in 1971, although the game 'Tennis for Two', also known as 'Pong', was available to play on the oscilloscope in the year 1950 (Smith, 2019). A device that a digital game operates on serves as a rule interpreter but is also an output for a more detailed graphics and more complex gameplay experience (Wankel and Blessinger, 2012). The introduction of the digital component to gaming has served to lower the entry level barriers for the player as the ruleset and the set-up are both managed by the software. The scope of the games available also increased, with the development of new technologies, especially 3D graphics, video games have achieved levels of immersion previously impossible to their analogue predecessors. Simulation programs have been not only employed as tools of pure pastime enjoyment but also as learning tools for the military (Yao and Huang, 2020), medical staff (Beal et al., 2017) and machine operators (Allerton, 2010).

With the internet being a ubiquitous phenomenon, it opens virtual games to the mass market. In the year 2016 the revenue of console and the mobile gaming industries combined exceeded the combined revenue of movie sales across all platforms. In developed countries nearly every household possesses at least one device capable of running videogames (Sweeney, 2021; Witkowski, 2021). With greater access and popularity of digital online gaming, the focus of gaming scholarship has shifted drastically from other forms towards online video games (Annetta, 2010).

While understandable, the distinction is needless, as video games are essentially a further development within the space of gaming at large and need not be considered separate. Given that gaming follows similar set of rules and principles regardless of platform, this chapter will remain platform-agnostic and the findings that pertain to one type of game are considered applicable to the others unless stated otherwise. However, in the final analysis the nature of different types of gaming for effective science communication and knowledge transfer will also be taken into consideration.

A note on the cross-culturality of gaming:

Gaming is not a phenomenon unique to any particular culture, which makes them useful vehicles for science communication. Games with contemporarily-familiar structure can be found through distant ancient cultures (Erasmus, 1950; Finkel, 2004). Many of the theoretical frameworks discussed in this chapter point to gaming behaviour as a function of human cognition and decision-making, which can also be observed outside of gaming proper (Huizinga, 1938; Kuhn, 2021; Pellis & Pellis, 2017). Traditional games are found in virtually every known human civilisation, and digital games are ubiquitous in developed societies, with massive global revenue and a lively international esports scene (Jenny et al., 2017). Different gaming cultures are present within different world locales (Cartlidge, 2022; Kikkawa, 2022) but overall, the media of gaming remain near-universal and this inquiry found no contriving levels of locale differences. As such, the findings of this chapter should be considered applicable regardless of the geo-cultural context.

Types of Games:

There are multiple ways to categorise games (Ruggill & McAllister, 2011). The exact method and paradigm differ depending on the goals of one's inquiry. Games can be perceived through the broad logical/mathematical lens of 'game theory', where most human choice-based phenomena are objectified as games (Shubik, 1983). It is an approach reminiscent of the broad scope of *Homo Ludens*. An example of a game that is understood by such framework is the 'Prisoner's Dilemma'. It is a hypothetical scenario, in which two subjects are acting without the knowledge of one another's choices trying to minimise harm, while maximising their own possible gain (Kuhn, 2021). There is the experiential framework of how the player engages with a game, and what type of experience it best emulates to them. This approach is more open-ended and prone to subjective classifications. For example, the game of "Darkest Dungeon" later discussed is commonly referred to as a strategy game, a roleplaying game and a "rouge-lite" based purely on the reviewer's experience of the game and similar games. 'Operational gaming', which Shubik (1983) further discusses, has more to do with the operations of economic systems rather than games as understood in this chapter.

As this inquiry considers games' suitability for science communication purposes, it will consider game design as an artform, with distinctions based on its medium. This is the most salient and practical approach as it is based on an empirical signifier (the game medium) and avoids the subjective experiential classifications, while also steering away from the detached, mathematical view of 'game theory'. It is an approach designed to help a maker make informed choices for their practice.

Traditional games:

The first (chronologically speaking) branch of gaming is 'traditional gaming'. Traditional games are most broadly games that do not involve an electronic device in their play. This is a broad classification but helpful no less for an aspiring game designer. Traditional games have a lower technological entry barrier for both the player and the creator. While requiring more investment of time and attention to learn the rules and keep track of the physical/mental play pieces, they also near-universally encourage human interaction (Jore, 2011).

Figure 2: Full 4-player set-up of the game ‘Belly Rumble’ created by Pawel Stachyra. It serves to illustrate typical elements of a traditional games: cards, dice, board and pieces. P photograph by Pawel Stachya.

Traditional games can be mediated through a variety of commonly used items. Cards, dice, boards with miniatures, and rulebooks are most common, as demonstrated in Figure 4. The same pieces can be used to play different types of games, for example, a French-suited deck of playing cards can be used, among others, to play ‘Blackjack’, ‘Bridge’, and ‘Solitaire’, which can be classified as (in order) a game of chance, a co-operative tactics game and solitary logic puzzle game. The rules of the play are most often contained within the rulebooks, although may be contained within the pieces, or be passed down through oral tradition. The space of play may be a table in case of a card game, a board in case of a boardgame, the theatre of the mind for a roleplaying game or an open outside environment for a live action roleplaying game.

Traditional games may be games of luck, skill, strategy or even physical reflex. Adversarial, competitive games are often referred to as war games. A quintessential example of such game is chess (von Hilgers & Benjamin, 2012). A competitive element is present within most games, even in cooperative games that do not include open player rivalry, players compete against the structure of the game itself (Zimmerman & Fortugno, 2016).

Digital games:

Conversely, the term ‘digital games’ refer to any game played through a medium of an electronic device. Videogames, compared to traditional games, have a higher technological and financial entry level requirement for their creators. On the other hand, the entry level is lower for the players. The computerised engine of the game handles most of the set-up and ruleset of the game, and there is no intrinsic need to require multiple players to be in the same location (Rot et al., 2022). Single-player digital experiences are more common with the digital gaming medium and the multiplayer game is most often facilitated through an Internet connection.

There is a wide range of scope between individual digital games available. Large game development studios produce ‘triple A games’ that are large-scope projects with budgets and credits often exceeding these of major Hollywood films (Iskarius, 2020). Examples could include the ‘Witcher’ (Culture.pl, 2018) or Senua’s ‘Sacrifice’ (NinjaTheory, 2017). Conversely, smaller studios tend to create smaller, more focused games like the ‘Darkest Dungeon’ (Red Hook Publishing, 2016; Cartlidge, 2022). That being said, party games and local multiplayer games are also present and enjoy some popularity. An example of a digital party game is ‘*Kahoot!’;* a fast-paced custom quizzing platform, which has been adapted for educational purposes on multiple occasions (Castro et al., 2019; Neureiter et al., 2020). Digital party games are an interesting example of continuity between different gaming media. While they are mediated by digital platforms, they are often played in a group of people within the same physical space same way traditional board games and card games are played. Often a digital game emulates the experience of a traditional game (e.g. Chess simulators or card games played through an electronic device).

While many games played on digital devices can also be played traditionally, the digital medium enables use of real-time gaming. Digital games often test the player’s coordination and reaction time as well as any more mental attributes. Digital games can achieve faster pace to that of the traditional games. It is possibly partly responsible for the emergence of the e-sports phenomenon, where the audiences can spectate the game in real time, as large team’s efforts are mediated, streamed and captured by the software (Jenny et al., 2017). Another, distinctive functionality of digital games is record-keeping – a game can automatically record and store data of any player’s action – as such digital games somewhat lend themselves to objective observation of human behaviour.

Serious gaming:

There exists a pervasive cultural perception of gaming being antithetic to productivity or even morality itself (Binde, 2007; Elequin, 2020; Laycock, 2015). Coming back to Huizinga's and others' theories of mastery of play, it is a harmful assumption. High-stakes tasks are commonly simulated through games, as a mean of training. Wargames were used to visualise and simulate combat since at least the Napoleonic era (Glick & Charters, 1983; von Hilgers & Benjamin, 2012). Simulators are used in training of medical professionals and machine operators (Allerton, 2010; Beal et al., 2017; Yao & Huang, 2020). The concept of games produced for the purpose other than enjoyment, or using pre-existing games for such causes is referred to as 'serious gaming' (Giasolli et al., 2006).

Less often, the process of teaching through the use of gaming is referred to as 'ludopedagogy', although it seems to be a recent term and mostly concerning formal education (Wareham Morris & McGowan, 2018). In this chapter, 'serious gaming' is defined as gaming intentionally for purposes beyond enjoyment. The opposite of a 'serious game' becomes a 'pure game', which is one played mainly for enjoyment. 'Serious games', however, are not as clearly delineated from the 'pure games' as 'traditional games' are from 'digital games', as games created for serious purposes may be found enjoyable by a wider audience, which may be unintended, or intentional on behalf of game's maker. Marketability and attractive gameplay are factors driving interest in game's serious subject matter (Brody, 2019). Table 2 is a table summary classification of types games based on the medium.

Summary table

Types of games as discussed in this paper:					
Game type	**Technology**	**Common Setup**	**Main Qualities**	**Examples**	**Number of players**
Roleplaying Game	**Traditional**	**Theatre of the mind, character sheets, rulebooks, dice;**	**Collaborative storytelling, creative licence, no defined victory terms, open structure;**	**Dungeons And Dragons, Shadowrun, World of Darkness**	**At least two;**
Boardgames	**Traditional**	**Board, boardpieces, tokens, dice;**	**Great variety of structure, approach, and timing, chance and skill elements;**	**Chess, Mah-jong, Entaglion, Monopoly, Pandemic**	**One to multiple;**
Card Game	**Traditional**	**Cards, counters, tokens;**	**Chance or skill focus, high variety, often collectible, portable;**	**Poker, Solitaire, Magic the Gathering, Rummy, Coup, Yu' Gi' OH!;**	**One to multiple;**
Miniature Game	**Traditional**	**Maquette board, miniatures, dice, measures;**	**High material/time investment, open modular play within the rule set, set on a 3d board; collectible/hobby aspect;**	**Warhammer 40k; Bolt Action, Carnevale, Rumbleslam**	**Two to multiple;**
Live Action Roleplaying Game	**Traditional**	**Real world locations, dress-up, accessories, often faux weapons**	**Cooperative or competitive roleplaying action, may or may not involve a form of codified combat and environmental putties, no clear victory condition;**	**Typically based on modified Roieplaying game franchises;**	**Multiple with multiple support staff and game-runners.;**
Megagame	**Traditional syncretic**	**Real world locations, game boards and maps, tokens and counters, attributes of a LARP. a wargame and a**	**Syncretic elements of LARP and boardgame. often played over long time within large or outdoor venues, may include digital l elements;**	**Extemporaneous;**	**Multiple competing teams, numerous support staff and game- runners;**
Video Game	**Digital**	**PC, Console or Mobile device with**	**Great variety and a large modern market, very dependent on the current state of technology,**	**World of Warcraft, Fallout 1, Candy Crush Saga, FIFA series, Niche, Darkest Dungeon;**	**Single player to concurrent millions of**
Augmented Reality	**Digital Syncretic**	**Mobile device or an AR headset.**	**Overlaying the digital imaging over a real-world location, often GPS tracking, often used**	**Pokemon GO, Kahoot! (arguably), Zombies, Run;**	**Most often massively multiplayer**
Virtual Reality	**Digital**	**Electronic device with a virtual**	**Disconnect from the surroundings, long history of experimentation, often used for**	**Flight simulators; VR chat;**	**Single player to massively multiplayer.**

Table 2: Example classification of games based on the medium.

Gaming as a medium of science communication:

Science communication is an important skill for future scientists in disseminating their research as well as informing both public opinion and policy (Donev, 2013). For the purpose of this discussion, 'science communication' is considered to be predicated on two values: 'fidelity' and 'coverage'. 'Coverage' can be defined as a combined amount and demographic of people engaged with the scientific material. 'Fidelity' refers to quality of the communication; it must be clear, approachable for the target audience, and not contrived. Approachability is predicated on both the delivery of the material and voluntary engagement with it on the part of the audience.

Science communication can be described broadly as exposing the target audience to scientific concepts and information (Donev, 2013; Illingworth & Allen, 2016). The audience can be reached through magazines, art exhibitions, content creation and broadcasting/podcasting, and public engagement programmes. With the advent of common internet access, science communication is also increasingly open to private individuals, rather than educational organisations, both to produce and consume (Fox et al., 2021). The aforementioned vectors of public engagement are used to gain coverage.

While scientific knowledge is a field of open enquiry and debate, scientific facts may be defined with a high degree of objectivity, especially within the STEM fields (Kanyapasit & Srisawasdi, 2014; Tanghe, 2016). As such, a vector of science communication is required to be precise and accurate in its ability to portray the concepts and at the very least not to contradict the science with its messaging (Taddicken & Reif, 2020). An interesting dynamic emerges, where science communicators must balance fidelity and coverage. Questions arise: Can one make a scientific concept approachable? Does the popular appeal compromise the scientific value?

Scientific material can be provided through detailed verbatim exposition, but it can also be hinted at. The target audience must be specified and understood (Illingworth and Allen, 2016), and the target of the scientific communication outreach may instead be signposted towards the primary sources for their own further reading. The values of *pathos* (emotional appeal), *logos* (logical argumentation) and *ethos* (appeal to one's credentials) need to be measured and balanced for an effective approach (Braet, 1992). This can be somewhat simplified as: *pathos* drives popular interest; *ethos* uses authoritative sources to legitimise the message, and *logos* can be used to sway more expert and inquisitive audiences (Higgins and

Walker, 2012). Overall, good science communication needs to include a balance of the approaches predicated upon the knowledge of the audience (Illingworth and Allen, 2016).

Additionally, a distinction can be made between ‘inward-facing’ and ‘outward-facing’ science communication (Illingworth & Allen, 2020). The latter is congruent with the definition thus far and describes specialists communicating expertise to the often less knowledgeable broader public. ‘Inward facing’ science communication occurs between qualified scientists, through dialogue, conference and publications. A peer-reviewed journal article can be seen an example of ‘inward-facing’ science communication.

In relation to the ‘coverage’ of science games it would be wise to consider: how many people can a game reach? What demographic will the game be more attractive towards? Will people actively reach out and seek to play the game? (Illingworth and Allen, 2016). A game is a participatory art form, often demanding of a high time and emotional investment form its audience. Through a mixture of game-design, attractive artistic presentation, gripping narrative or the competitive thrill, games can captivate and often retain the players. Often, a ‘flow-state’ may be observed in a gamer, where the person involved in the activity loses the sense of self-awareness and time instead becoming fully engrossed in the activity at hand (Nah et al., 2014).

A science communication game has to not only appeal to a large audience, but it also has to directly and personally involve each player to a point of them making a time investment assuming the gamer identity (Annetta, 2010). The gamer identifies and is identified as a part of the community of fellow gamers. They also invest their time and effort to increase their mastery of the game. As such, a game must have a toolset appeal to a diverse enough selection of potential players each directly, accounting for different tastes and preferences. Some may be drawn by the aesthetics of the game, some by the narrative, and some by the competitive experience. Likely every single part of the game will never be fully appreciated by a single individual but is necessarily included as to attract the multitude.

Games as educational tools:

One of the major loci, where science communication occurs, is within educational institutions. While the exact approaches will vary by location, culture as well as the school type and the jurisprudence of the teacher, overall communication of scientific knowledge, impartment of skills and cognitive development can be described as consistent. Cross-culturally, a student is challenged to acquire skills and information to better function in the society as an adult.

The process of learning occurs within or without the institution, however, within the formal setting examination and accreditation are introduced to track student's progress. The accreditation and examination results are imparted upon a student not unlike an initiation ritual (Illich, 1971). By progressively challenging the learner of any age, facilitating their cognitive development, and equipping them with skills, the learner can be progressively exposed to more demanding tasks and material, as described in the scaffolding theory. Here, the learner learns things in their proximal zone of development and expands their knowledge outwards towards erstwhile distant subjects (Vand Der Stuyf, 2002). Within such framework, a structure can be outlined where a learner progresses from cognitive development and through the skill acquisition into being able to critically engage with scientific subject matter presented to them (Walker, 2003). Eventually, a learner being knowledgeable and competent enough can seek out and interrogate the information they require (Illich, 1971).

There is a constant theme of dissatisfaction with the modern educational system, with it being reported to be antithetical to creativity and individuality of the student (Illich, 1971; Collins, 2004; Day-Black et al., 2015). In a traditional classroom, students are obliged to learn at a pace that might compromise the needs of some (Wong and Csikszentmihalyi, 1991). Such compromises tend to leave either party with their needs unmet (Illich, 1971), conducting and directing their own research based on priorly obtained knowledge (andragogy) (Lage, Platt and Treglia, 2000; Betihavas et al., 2016) and squandering the potential for transformative teaching approaches. This might unfairly disadvantage those outside of a privileged socioeconomic position (Darbyshire, 1993; Sandlin, 2005).

The search for new experimental learning techniques implies the active role of the teacher (pedagogue) (Darbyshire, 1993), with in-demand University degree courses calling for new innovative methods for learning (Day-Black et al., 2015). Moreover, approaches transcending the pedagogy-andragogy dichotomy between leading the learner and leaving them to lead themselves are required.

Multiple benefits of a gamified approach to learning exist. An example would-be problem-solving focus (Linn, 2004), where instead of memorising the material, students actively engage in learning as the educational subject matter becomes crucial to the competitive success of the player. Additionally, as games are a structured experience, they offer better conceptual convergence. In their conference proceedings, Kanyapasit and Siraswasdi (2014) report an educational issue, where students would all claim to acknowledge and understand the exact sequence of the prophase mitosis within the cell cycle, yet a significant portion of them would give divergent answers incongruent with the instructional material. The paper later goes on to propose a digital game learning framework to help ameliorate the issues. An organised, sequential gameplay is proposed as a framework to which attach the exact steps of the cell cycle sequence. Games, often relying on a particular turn order and a particular sequence of moves required to win, can lend themselves well to intimately simulate complex processes in a way that makes the player familiarise themselves with process in question.

***Ludopedagogy*:**

Combining the derived definitions of gaming, science communication and learning, the concept of 'ludoeducation' (Giasolli et al., 2006) can be introduced. Arnetta (2010) proposed a framework for designing video game and virtual reality experiences (figure 5). This model concerns multiple facets of gaming experience nestled within a hierarchy from the most fundamental being *identity*, to the *instructional* being the broadest. The 'external' facets are predicated on the success of the 'internal' facets and only with the successful implementation of the more intrinsic elements of gaming, the educational purpose may be met successfully.

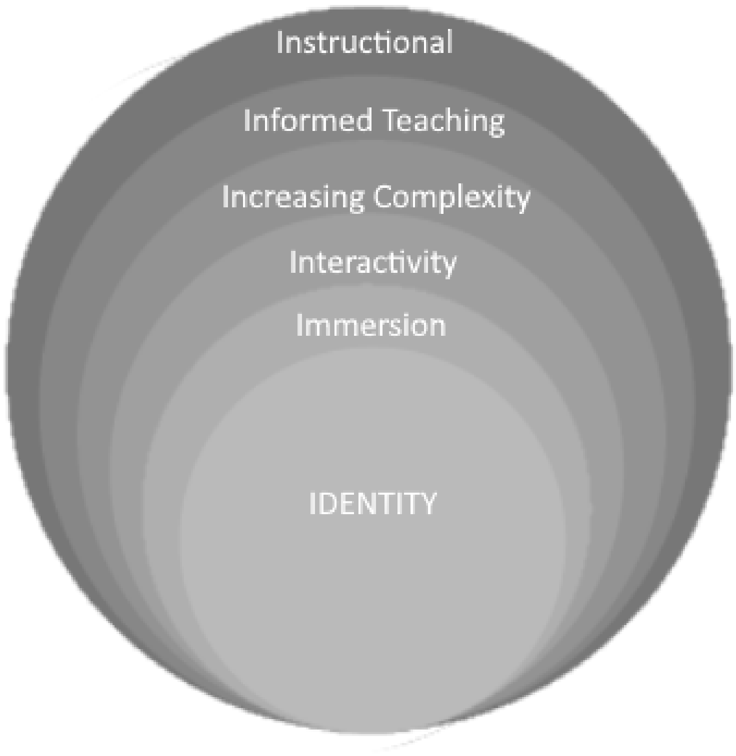

Figure 5: Diagram repurposed from Anneta (2010) publication by Pawel Stachyra. The model argues building upon the core gaming elements of (Identity to Increasing Complexity) to support the subsequent implementation of educational content.

'Identity' is a crucial factor, that may not seem obvious. The player becomes a subject within the game, either within oneself or within a group. As such the experience becomes personal to the student and promotes higher engagement. At the same time, every player having played the game gains a shared experience that has been resolved within the same rules and parameters. Players with otherwise divergent processes and backgrounds can all relate to this standardised experience. There emerges a development of a learning culture – the players become a community with its internal loyalty and accountability. In Strickland and Kaylor's (2016) experimental study, this theoretical framework seems to be validated by nursing students involved in a megagame reminiscent of a scavenger hunt. The students not only were motivated to perform and learn a variety of practical and theoretical tasks but were further encouraged to aim higher to 'win' the game as members of competing teams.

Another facet of note that runs through all gaming experiences is the competitiveness. 'Increasing Complexity' is an expression of challenging gameplay. The player is encouraged (again, through their identity as a student or a group member) to tackle progressively more challenging tasks or opponents (Castro et al., 2019; Vorderer et al., 2003). It is not unlike the very nature of learning, although the motivation does seem to occur more intrinsically rather than through the external means used in classic education (grades, deadlines, standardised testing). Moreover, the increasing challenge may be beneficial for gearing the challenge toward students' individual levels. It is the student themselves, who seeks out harder challenges and opponents, once mastered their current level. This seems to be congruent with the observations of Kanyapasit (2014), where an emphasis on critical problem-solving is brought up as a benefit. When engrossed within a game, the player is encouraged to involve their higher critical learning faculties beyond memorisation and recall (Davidson & Candy, 2016).

In previous research projects, first author, Pawel Stachyra has repurposed the Anneta model (Stachyra, 2021) and added some nuance to allow for non-digital games, as well as delineated the pure game from a serious game within the framework's boundaries. This is presented in figure 6. With terminology introduced and definitions established, case studies of gaming for science communication can be discussed and analysed.

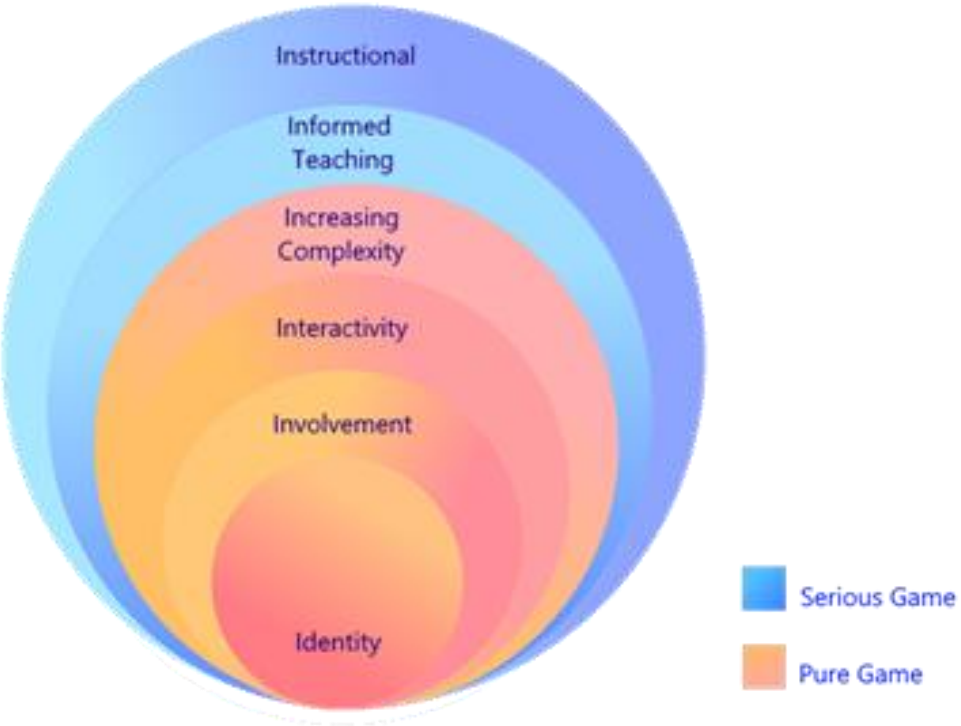

Figure 6: Annetta's model repurposed and updated by Pawel Stachyra. Distinction is made between "pure gaming" principles and the "serious gaming" principles. Serious gaming effort needs to be based on well-implemented pure gaming core.

Science Games Case Studies

When considering science communication through game, the most obvious games to discuss are those made explicitly for such purpose. Games are often used as an attractive object to drive attention for both students and the public alike. Additionally, the structure of a game is usually fixed, thus lending itself to explain scientific procedures clearly. In relation to games as science communication tools, the educational outcomes of the subsequent case studies will be judged on their achievement of skill-impartment, cognitive increase, and communication of science.

'Niche' – a high fidelity science with enjoyable gameplay:

An example of a game with high scientific fidelity that achieved a full implementation of 'pure' gaming design values is the video game 'Niche' (Stray Fawn Studio, 2017). The game was originally developed as an honours degree project but moved on to become a popular standalone title as the author employed a team of developers. The core principles of ecology, including Darwinian selection, genetic drift, and adaptations, were implemented with a high degree of fidelity into the game experience (Stray Fawn Studio, 2017). The player assumes control over a species of animal, called '*nicheling'* trying to adapt and survive within changing environment. Despite being a marketed game with a popular appeal, the game remains accurate to the core tenets of its scientific subject matter. The main aim, however, is providing an enjoyable experience. As such, 'Niche' may be considered a 'serious game', depending on the intention of using of it. The game holds favourable reviews with both pedagogues (Bristol, 2021) and gamers (Sinclair, 2017; Valve Software, 2021).

'Entaglion' – a traditional game about quantum computing:

Another example of a well-implemented serious game is a quantum computing boardgame titled 'Entaglion' It is a simple traditional boardgame dealing with an otherwise high-scientific concept that helps to explain the process of quantum computing, met with generally favourable reviews (Brody, 2019). 'Entaglion' can be classified as a 'serious game' as it was created with a goal of explaining a scientific concept, but it can also be seen as a 'pure game' in the manner it is being marketed to the public.

Interestingly, 'Entaglion' reverses the commonly used approach of using narrative rather than play elements to communicate a scientific process. The narrative setting of the boardgame is a rather generic science fiction universe, with the players tackling the issues of space navigation. The scientific material is instead contained within the gameplay system., and the success of a player is predicated upon mastering the choice sequences present on the game board. Said sequences are representative of the *Boolean* logic gates used within the field of quantum computing. The scientific accuracy was rated positively in Ashoori's (2018) study, which saw stringent playtesting and iterative design rounds of the game, under the supervision of experts within the field of quantum computing, and by experts who field tested the game (Brody, 2019). Additionally, the game has been met with enthusiastic reviews and some commercial success (Brody, 2019)

Game design can lend itself well to communicating high-fidelity, high-specificity hard science. The sequential, structured nature of play lends itself well to making the player intimately follow along a complex process (Kanyapasit & Sirsawasdi 2012). The enjoyment factor of the game keeps the player motivated to do so. Some caution must be taken by science enthusiasts making games as to not underdeliver the gaming aspect of them, least the game becomes more of a study help than an actual ludic experience.

Gaming within a science education setting:

Ludopedagogy within nursing education is common with research studies dating back to 1960s. Nursing education relies on both teaching practical skills as well as theoretical knowledge. As such different aspects of ludo pedagogical approach can be tested. Day-Black et al. (2015) cited problems within the nursing classroom included learning materials being considered unappealing and difficult to relate to, with a desire for alternative, interactive approaches being expressed. Given that nursing is an in-demand occupation, efforts have been made globally to facilitate and optimize the development of future workforce within the sector using games.

Hijacking 'Kahoot!' for education purposes:

The first example comes from Spain, in the University of Valladolid (Castro et al., 2019). The faculty took it upon themselves to improve both the engagement and the educational attainment of the students. Concerns were expressed regarding increased intake of students and decreased funding. As such an educational tool of high efficiency was required and the game, '*Kahoot!'*, was repurposed for the task. '*Kahoot*!' can be described as a customizable mobile phone online quizzing platform, where players track their progress by 'gaining experience' for correct answers. As such, without being purpose-built for nursing education, it can be described as a pure game 'hijacked' for the purposes of learning.

The study found slight improvement in test results but more interestingly, the games' structure let the researchers easily measure response times for each question and compare it against the accuracy, providing additional data points for analysis. The questions that took less time to answer were near universally found more often answered correctly. The authors conclude that gaming can indeed prove a useful tool for education as it increases engagement and interaction, as well makes for more effective testing (Castro, et al., 2019).

The findings of the study were later expanded upon and confirmed in another study (Nerueiter, et al., 2020), which not only implemented the very same game in an educational setting, but also managed to produce a robust experimental study of the game's efficacy. The reported time for answering decreased by roughly 50% and the median attainment of correct exam answers increased from 45% in the control group to 76%. It is a stark, marked improvement and the gamified approach seems to not only better command student attention but improve teaching outcomes overall.

In case of the Nerueiter's 2020 study, it was used on medical student cohort and suggests '*Kahoot!*' and similar games can be successfully repurposed for multiple divergent fields of study. The instant feedback is provided not only to the students but also to the faculty and can be used to inform both the staff and the student themself on what questions seem to be a struggle. It may point to a phrasing error, or a particularly complex, perplexing part of the material (Neureiter et al., 2020). Overall, quizzing platforms seem provide near-ready solutions to lots of educational problems. The parameter of a game as an activity providing instant feedback (as in Arnetta's 'Interactivity' value) is exemplified here. Additionally, as Castro et al. (2019) reports, the increased engagement between students, discussing answers and consulting one another. This community building quality, in turns seems to reflect Arnetta's 'Identity' value, also remarked by Huizinga and Kanyapasit (2014).

The described uses of *'Kahoot!'* for science education represent a use of a pure game for the educational purposes. Interestingly, a similar study with similar results was performed using the open rules of the quizzing card game '*Jeopardy'* (Boctor, 2013). As such, by making the quizzing environment more interactive and providing the player identity to the learners, a group of learners may be better engaged through use of traditional gaming mediums. The only loss in that case would be the loss of direct digital feedback to the educator. A similar approach was implemented with a game of '*Deal or no Deal'* for the mathematics students, for the results of better engagement and retention (|Chow, Woodford and Maes, 2011). Overall, there seems to be a strong toolset of pure gaming titles, that may lend to an educational instruction.

'Transcription' boardgame – a game as a biomedical visualization learning tool:

'Transcription' is a board game focusing on the subject matter of RNA transcription, and was a co-operative experience with no competitive element between the players. (University of Dundee, 2012). The game was tested over a few years and was fabricated in multiple copies for internal use in tutorials. First author, Pawel Stachyra, being a student at the University at time, had an opportunity to play this game. In teams, players took turns to 'move' the cell cycle forward. There was no single or team victor by design. On the other hand, the progression of the game sequence was closely analogous to the sequence of the RNA transcription. Different sub-cellular elements were represented by a variety of custom tokens, counters, and board pieces. The game resolved by skill once the entire sequence has been completed as represented by a desired end-configuration of board pieces. The boardgame thus became more of a simulation than an actual competitive experience and was not further casually used by students.

To our knowledge, there was no use of the game outside of the tutorials, and the game was not released to the public or mentioned in any scholarly publication other than the university website. It is an interesting example, as on one hand the structure of a traditional game lent itself well to portraying a scientific process with high granularity. In Anneta's model, the game provides 'Informed Teaching' and 'Instruction'. The board with multiple representative pieces also provided 'Interactivity' in a general sense, but the parameters, the moveset of the game did not allow for experimentation with the gameplay. Here, 'Increasing Complexity' was not achieved in the game design. The lack of competitive element has removed any stakes for a player to assume the gamer identity, and the same starting layout always led to the same ultimate end-state, meaning that the game did not allow for increasing mastery within the game.

Overall, the game did not meet most of the core (pure) gaming parameters, while achieving the distal, serious parameters. It is an example of a game with high accuracy scientific material but missing some of the basic game design considerations – a common error present in games made by scientists and not game designers (Zimmerman & Fortugno, 2016). From personal experience playing the game, it could be improved by adding an explicitly competitive element (either vs other players or a timer), as well as adding a degree of randomness to the set-up as to add a dynamic challenge.

Indirect science communication - designing a killer plague to save lives:

Sometimes, games not necessarily intended for a serious purpose, can also serve as science communication devices. One such game is 'Plague Inc.' (Ndemic Creations, 2021). It is an example of a very popular pure game available on mobile devices and PCs. The player takes control of a deadly pathogen and undertakes a somewhat accurate epidemiological simulation to wipe out the humanity. It is remarked that the transmission vectors and the evolutionary adaptations of the virus are very reminiscent of those in the real-world and the creator was even invited to speak before the American healthcare authorities (Microbiology Society, 2016). The game became very popular early in the SARS-CoV-2 pandemic and arguably helped propagate correct attitudes towards disease spread and control. A very interesting observation is to be made in case of those three games.

Through the ‘Identity’ principle, the gamer is put in unusual, unrealistic positions (controlling a disease or a species) but because of the implied unreality and detachment of the experience, the suspension of disbelief is present and helps mitigate the problem (Seraphine, 2018). Despite this, ‘Plague Inc.’ is credited with a positive impact on social attitudes regarding epidemiology globally, both during the Ebola crisis from 2013-2016 and in the early stages of SARS-CoV-2 pandemic (Jiang et al., 2021; Mitchell & Hamilton, 2017; Peng & Bai, 2021).

Modelling of scientifically sound attitude alongside creative engagement with the subject matter are cited as benefits of using the game (Peng & Bai, 2021) . ‘Plague Inc.’ represents how a game may use its popularity as a vector of correct scientific terminology and attitude, as long as it as references sound scientific material. It is perhaps an underused avenue of science communication, where informed efforts can launch off the momentum of a popular marketed title. The public primed with the correct terminology and introduced to key concepts may be better suited to engage with scientific outreach efforts in the future.

Driving interest in science ethics through gaming:

Narrative is one of the most powerful tools available to a science communicator. The introduction of in-narrative profound ethical choices in games is not unlike the established educational practice of discussing case studies to promote critical thinking (Popil, 2011). Games indeed seem to display a continuity with works of literature, particularly science fiction, that take their longform nature to slowly and thoroughly explore difficult scientific subjects within a casual, entertaining setting (Barnett et al., 2006),

The video game ‘Alpha Centauri’ (Firaxis Games, 1999), through its minimalistic narrative design, points the player towards ethical questions that include the value of individual vs collective, the ethics of independent AI’s, biomodification and cloning of humans. The short, often ominous cutscenes do not provide answers, but rather phrase and rephrase the question of profound ethical implications. Given, that games often include complex, well-referenced narratives, it is possible that video game carry the function previously covered by science fiction novels that popularised the subjects of science. In this aspect, a science communicator, artist and a game designer may not only reach, but also over time create an audience ready to engage with the hard science topics (Illingworth and Allen, 2016). A study of prescriptive narratives in science communications, seems to further build upon the point of the narrative's potential to build and model behaviour, on top of promoting dialogue (Downs, 2014). The most promising aspect of the employment of such narratives is that they can remain independent of the game mechanics, thus offering more of a freedom of expression for the author (Seraphine, 2018).

Upstream interactions of games and science – inward-facing science communication:

Lastly, games can also be used in inward facing science communication. Having previously discussed accidental and/or indirect science communication, this section will conclude with some impactful examples of games educating the educators. As previously mentioned, games and especially the online games have an innate ease and reliability of recording player's behaviour. Every single decision made by each single player is traced, noted and stored, often in massively multiplayer games with high millions of concurrent players active at one time. As such, digital worlds provide one thing scientists take interest in – large datasets. Gaming behaviour of a player is not as divorced from their real behaviour as one could suspect. The player-identity is strong as per Annetta's or Huizinga's approaches. The player assumes the role of a subject in game and makes large time, attention, and financial investment into their play behaviour. Harm to their online avatar is a thing actively avoided and thus players act in the virtual world with a self-interest not unlike that displayed by them in real life (Toh, 2021).

Games can be used to derive highly data-rich models of human behaviour, and the most famous case is likely that of the 'Corrupted Blood' incident in World of Warcraft (Blizzard, 2004), one of the most popular digital massively multiplayer online (MMO) games with around 1.5 million concurrent active players. The 'Corrupted Blood' incident occurred to the game developer's surprise and was not an intended part of the game experience. Players realised that a particular 'Non-Player Character' (NPC) raid boss afflicted their characters with a simulated disease, which damaged their character's health and subsequently spread to nearby other characters. The damage was significant for a highly developed character but immediately deadly for any lower-level character. Some malicious actors began to preserve the ‘disease’ and carry it into large gatherings of players; auction houses, guild halls, town squares, to spread it. What followed was a turmoil within the virtual world, with major population centres abandoned and weaker players fleeing to more remote areas in the game. Eventually, as the virtual pandemic raged on, entire servers became depopulated and hostile to the digital life (Smith, 2012). Many different behaviour patterns have been observed. Some players started displaying altruistic behaviours and helping the weaker players survive. Others would intentionally keep infecting one-another to preserve the plague and release it again upon other players. Self-organised quarantines were imposed, and certain vistas blockaded. The behaviours were used to model future pandemic and became a primer for the epidemiologists to begin tackling the covid crisis later (Kriz, 2020), The significance of this event, is that an unprecedented of unintentional participants have provided data of their movement and reactions within an environment, where their action could be easily catalogued and preserved for the future scientific research. Future observation of online communities became recommended as the effect (Girish, 2019; Smith, 2012).

Another example of using gaming to inform the scientists is that of the ‘Phlyo Project’ – a citizen-science platform presenting as a puzzle game for the voluntary participants (Kawrykow et al., 2012). While the game itself was divorced from the scientific subject-matter, it presented the player pieces of a DNA sequence in the form of a logical puzzle. Players would look for patterns matching the coding regions of the DNA codes and be scored well on the speed and efficiency of finding said patterns. Scientific data produced was considered of better quality than the mechanistically-obtained data and was supplied readily at high efficiency (Kawrykow et al., 2012). Given, that players often willingly give their time and focus to games, the player base remain somewhat of an untapped resource that the gaming medium offers. It is a promising avenue to explore, as long as the game design can be used in such a way that the game output becomes sound scientific data, while providing entertainment to the player.

Examples discussed in this section, provide some more in-depth focus on how a game can indirectly promote certain attitudes and drive informed conversations. The stand-out example is that of the ‘Plague Inc.’, where a game accidentally provided the general public with a primer on the epidemiology education, especially communicating the potential downfall of poorly implemented policies and safety measures. The impact of the game on the public response to the SARS-CoV-2 pandemic may never be truly explored, as such studies would face a strong survivor bias. A game narrative is free to be shaped however the author see fit and carries a potential of subtle, non-confrontational presenting of ideas to the public, although a manipulative, almost-propagandistic approach should be used responsibly, with caution and humility (Kikkawa, 2022).

Developing a science board game: "Belly Rumble: a microbiota tactics"

Having suffered screen fatigue and low social interaction after two years of SARS-CoV-2 pandemic lockdowns, first author, Pawel Stachyra opted to create a traditional game to help others learn about the gut microbiota. He was initially inspired by an existing boardgame, 'Quantum' (Zimmerman, 2013). In particular, he enjoyed how the game re-imagined the use of dice as counter and board pieces as well as random number generators, and envisioned a game dealing with the subjects gut microbiology, where dice value spread over the game board would signify living organism density area. Given the possible adversarial interactions between players, he settled for a strategy boardgame using cards and dice as props.

Initially oblivious to much of the terminology within the field, Stachyra approached the subject as a gamer himself, focusing more on game design and the experiential terms of play. Reading Zimmerman and Fortungo's (2016) developers reflections, the idea of making the game a competitive experience was reinforced, while driving interest, pointing towards sources and not contradicting the science (Brown, 2012; Taddicken & Reif, 2020). The gameplay needed to be 'fun' and engaging; therefore a simple game play was initially devised. It comprised an interplay of unit count on the dice (representing bacteria density) with different evolutionary pressures, adaptive strategies and random events operated by cards. The game's artwork was highly stylised with anthropomorphised bacteria (figure 7) and stylised, colour-coded modular board pieces (figure 8) to represent the transverse sections of the small intestine. The game cards produced for the Belly Rumble also included QR codes to relevant scientific and gameplay information to encourage fact-checking (figure 9).

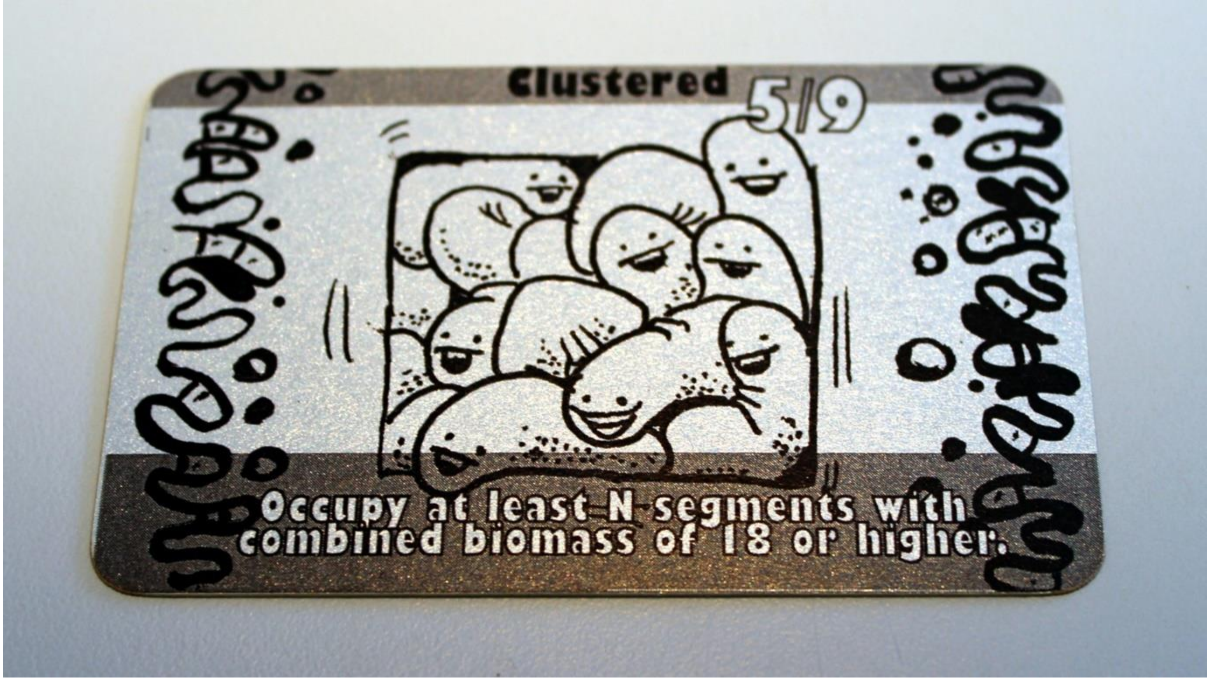

Figure 7: Game card produced for the Belly Rumble featuring anthropomorphised bacteria. Photograph by Pawel Stachyra.

Figure 8: Belly Rumble game set-up (3rd prototype). Dice represent different bacterial strains (players), and coloured modular board represents the intestinal sections. Each playaer can gain up to two gold "adaptation" cards and has two secret victory conditions (silver). Photograph by Pawel Stachyra

Figure 9: Game card produced for the Belly Rumble displays an interplay of the narrative and ludic elements of a game piece. After including all the game-relevant information any type of story can be conveyed through artwork, wording and in this case- QR codes. Photograph by Pawel Stachyra

In the development process, an AGILE approach was used, meaning a minimal functional product was created, tested with participants and then improved upon based on feedback in a cyclical manner (Dingsøyr et al., 2012). There were at least two major iterations of the game made after issues were identified through initial playtests with students from the 2020-21 cohort studying for an MA in Art in Science at Liverpool John Moores University. For example, the dice count was uncapped initially but later capped because it needlessly slowed down the gameplay, required unfeasible amounts of dice for a physical copy and contradicted the limiting nature of ecological niches (Qin et al., 2010). Game was designed to accommodate between two and four players, however it seemed to have the best balance/dynamics in the two player variant.

The game play used a turn-based gameplay, where players roll a number of dice based on the gut area their 'bacteria' control to use it as biomass. Evolutionary adaptations and strategies are picked by players using cards with both their in-game effects, comic illustration and often QR codes linking to relevant research. The main goal was to communicate science through narrative and structuring the gameplay as to not give perverse incentives or contradict the subject matter, following the recommendations of Brown (2012). Three aims were developed that sought to:

1. Provide enjoyable gameplay experience that players would seek out in their free time.
2. Drive interest in the subject and link to relevant scientific material for self-study.
3. Encourage and drive conversations about the subject between players.

In the development of the game board itself, there were considerations of board pieces (pre-existing die) fitting, as well as the board size for portability, therefore a modular design and a compact size was opted for. The complete boxed set of the game with the instructions, cards, board and dice was used in five in-person playtests. The final version of the game is available to download, including its ruleset and templates to fabricate the board pieces and cards in the spirit of open-source sharing on the project's webpage (https://pstachyra6.wixsite.com/website/work).

The dice were ordered from online resellers and the smaller 12 mm size was used for the sake of portability as opposed to more common 16 mm. Remaining pieces were fabricated using a Fab Lab - a local makerspace. The board pieces were cut from MDF using a laser cutter, after being printed/painted on using a silk printing technique. The cards designs were initially hand painted and then digitalised and added text was added in Adobe Illustrator. The card material was 180 gsm card stock and large gantry printers, and laser cutters were used to produce cards off the designs. There were multiple learning curve moments involved. Stachyra had to learn the practicalities of silk printing, operating a laser cutter with the associated software and then problem-solve the printing orientation and spacing of cards. What is heartening, was that discounting not insignificant supervision and advice of the maker space and print room staff, the game was successfully fabricated within two to three weeks from the first physical prototype (figure 10). Moreover, these designs were easily recorded and saved for further reproduction and iteration. It should be promising for any single practitioner or a team thereof that considers developing a traditional game – it is achievable, relatively simple and cost-effective in any locale with a functioning maker space.

Figure 10: All the board pieces, dice and cards assembled. The entirety of the game fits in an a5 footprint box. For the reference each MDF board square has a side of 5.5mm. Photograph by Pawel Stachyra.

‘Belly Rumble’ – playtests and reflections:

During the game’s development phase, closed playtests were performed online with peers during the 2020-21 UK lockdowns who gave informal verbal feedback. Between April and August 2021 playtests in an experimental setting with participants face-to-face in social public venues such as coffee shops took place (figure 11). Ethical approval was obtained from Liverpool John Moores University’s Research Ethics Committee (21/LSA/013) and qualitative feedback was gathered. Participants comprised different demographics and experience levels. Five playtests ran with 10 different participants and combinations thereof. The shortest complete playthrough took 24:37 minutes to resolve (two-player variant of the game), while the longest (four player variant) took 1 hour and 47 minutes. In every game played, it successfully concluded. The players left each playthrough commenting on the gameplay and discussing their strategies for the next playthrough. This hints at the successful implementation of the ‘Increasing Complexity’ principle discussed by Arnetta (2010), as the players were able to grasp the game rules and assume their gaming identity with their goals and possible moves.

Figure 11: A two-player playtest of Belly Rumble at Melodic Distraction, Liverpool UK, during the summer of 2021. Photograph by Pawel Stachyra and included with consent of Dr Lee Haines (pictured).

An anonymised online questionnaire was distributed to gather feedback. While the results were overwhelmingly positive, the sample size is small with limited diversity. For example, only three out of ten participants identified as women. It is uncertain, how large the effect of the sampling bias was, but overall, some observation can be made based on the feedback and the author's own experience running the game tables.

The game did successfully conclude in each testing run, for the 2nd and 3rd prototype version. The parameters and rules were simple enough for the players to grasp and build upon. The initial apprehension about engaging with the rules, would eventually dissipate as the players tested the boundaries of the gameplay. It was observed that novel, unpredictable strategies devised by the players and the discussions would ensue after the game regarding the course of action in possible future playthroughs. The competitive element was well received and seemed to drive the enjoyment of the game. The player's gender did not seem to affect the experience, regardless of the pre-concieved notions of competitiveness between said genders. The game would become challenging and engrossing around the 2-3rd round where the conflicts would begin occurring and players would attempt to close their victory conditions.

The audience that was more knowledgeable about the subject matter of gut microbiota, would remark that the gameplay is reminiscent of something they would imagine the gut ecology to unfold as and would not only recognise scientific references, but also propose some of their own into the future versions of the game. The subjects would universally report increased awareness and knowledge of the subject, although a less subjective measure should be included in the future investigations to avoid biases. Further testing in a more neutral environment with a wider demographic range of participants could help improve the data reliability. While, an online survey is appropriate for the purposes of the study, it sacrifices the free-form feedback previously gained in the closed development tests. For further testing the two methods should be cycled and supplemented. Lastly, the game had some balancing issues for the 4 player variant, where the turns would take long for the plyers to conclude and some victory conditions were much simpler to achieve than others. Such issues could be only addressed with continuing playtesting and iterations, and the authors are confident they can be addressed without compromising the core gameplay.

Overall, the game has managed to fulfil or show a promise of fulfilling the stated objectives. The robust theoretical framework of Anneta's model is credited, but also free-form reflective journals of Zimmerman, with guiding the authors through the process. The fabrication itself was also relatively simple with the help of the maker space staff and the modern consumer technologies and hence was more of an afterthought to the actual game experience and messaging.

An interesting sidenote was the mystique associated with me making a game. Play testers would usually display some awe at the process of me designing, producing and delivering a game. For the authors this process was deemed to be realtively easy, given their prior knowledge of the theory and practice within the field. It should be a promising prospect for the future ludopedagogists – as long as the core gaming values are delivered, the scientific expertise can be layered freely and creatively on top of them and the enjoyment factor refined and improved enough to make an attractive, engaging communication tool as will be discussed below.

Discussion

From analysis of the case studies in the sections prior, this section will discuss five promising qualities and three pitfalls of games for science communication to advise those considering games as their mode of engagement.

Promising qualities of games for science communication

Dynamic Complexity:

A game meets the learner at their level and provides a dynamic scaffolding, where the player raises up to new challenges posed by the game, and in turn seeks further challenges while their mastery of the subject increases (Annetta, 2010; Vand Der Stuyf, 2002). The progression pace becomes personal and perhaps more reflective of player's skill level.

Feedback Stream:

Performance within a game can be easily tracked both by the player and the facilitator (Castro et al., 2019; Nerueiter, Klieser and Neumayer, 2020). The player is constantly made aware of their progress and performance throughout the game (Kiili, 2005) so they either are reassured in their performance or notified to immediately seek assistance. More interestingly, feedback in a digital gaming setting can also be collected and tracked by a facilitator or educator, to help further improve the learning experience and knowledge transfer and identify the areas in a need of improvement. As such, some digital games can create complex databases of traceable information as was exemplified in previous examples of MMO games (Belaza et al., 2020; Girish, 2019). A feedback stream can be used by scientists themselves to derive insights, and the player can be nudged and guided towards correct attitudes through a game system.

Identity Commonality:

A game builds a community and commonality between the players, with them participating in a self-same structured experience within the same parameters (Huizinga, 1938; Annetta, 2010; Kanyapasit and Srisawasdi, 2014; Tanghe, 2016). It also provides a neutral exploratory space perceived as detached from real-world consequences. As such it promotes more bold, risk-taking and co-operative approaches together with well-natured competitiveness (Zimmerman and Fortugno, 2016). This helps demystify and reduce stress in learning a new subject, which becomes enclosed within the parameters of the game (Annetta, 2010). The 'commonality' value becomes important when dealing with complex scientific processes as the gameplay can be made analogous to the process itself – thus giving the player a practical example of a highly complex process as it was achieved with both the ‘Entaglion’ and ‘Niche’ games.

Incidental Exposure:

Games with rich narratives expose a player engrossed in the pure game experience to whatever subject the narrative may include (Davidson & Candy, 2016; Liz, 2003)(Liz, 2003; Davidson and Candy, 2016). As such, the players may become exposed to complex scientific ideas in a non-confrontational manner over the span of hours. This promotes self-directed inquiry and help shape the future of discourse by equipping the player with the vocabulary, motivation, and knowledge on the subjects (Illingworth and Allen, 2016). As such, designing scientifically informed game narratives may come to the forefront and build a future audience rather than identify an existing one, as with the ‘Plague Inc.’ game that informed about large player base about the concepts of epidemiology (Peng & Bai, 2021).

Cognitive involvement:

While games are considered a pleasant experience, and through their identity they are somewhat easier approachable than real-world tasks they still pose a challenge (Huizinga, 1938; Kanyapasit and Srisawasdi, 2014; Zimmerman and Fortugno, 2016). Such challenges promote the player to cogitate at their peak capacity, including problem solving, critical thinking and states of flow. More complex tasks can be broken down and challenged within a game. Through direct feedback players build confidence in their independent thinking and problem solving. It also provides a scaffolding structure, where the players can practice their critical faculties before tackling practical tasks or exams (Vand Der Stuyf, 2002). A detailed example of a proposed use of games and puzzles to prepare for introduction of more complex subjects, such as, cryptography and quantum computing, is discussed in a guideline paper by Moursund (2006).

Equity:

Having a shared experience, which tailors itself towards the player’s needs and means, promotes and enables a more inclusive learning experience, especially for players with learning disabilities or divergent learning styles. Gamified interventions have proven successful in assisting disabled students (Sholz et al., 2008) to perform at higher levels than they would otherwise. Additionally, traditional games can be developed and delivered in settings that may not afford fast broadband internet due to their low technological requirement. This potentially serves to improve education in less developed countries.

Shortcomings of games as a science medium:

Over-reliance on gaming:

A ludopedagogical approach is tempting to facilitate learning of complex science information, however, it may not be the most appropriate vehicle for knowledge transfer. Sometimes the game overshadows the learning (Christians, 2018; Wan and Chiou, 2006; Mauri et al., 2011), and successful implementation of a gamified approach should be seen as an additional tool and not a replacement for other modes of learning (Sholz et al., 2008; Chow, Woodford and Maes, 2011; Boctor, 2013; Kanyapasit and Srisawasdi, 2014; Castro et al., 2019; Nerueiter, Klieser and Neumayer, 2020).

Any form of science communication should lead the audience towards the further reading (Illingworth & Allen, 2020). It is simply unfeasible to expect the audience to derive fully nuanced understanding of the subject from just one instance or medium of communication. Games can be used to prime and energise the audiences but there needs to be further reading and clarification presented. A well-intended game may become a pastime and a distraction to knowledge transfer if not supplemented with instruction, information and further progression.

Poor game design:

Another pitfall is poor gaming design. Through too narrow focus on the learning material or foundational mistakes in the designer approach (Zimmerman and Fortugno, 2016; Gallegos et al., 2017) a game may fail to engage players. As observed with unstructured math learning, different students may develop wholly different processes, which prove valid and functional learning (Nunes, Carraher and Schliemann, 1985; Saxe, 1988), unless regarding a process-oriented subject (Kanyapasit and Srisawasdi, 2014). Otherwise, the engrossment of a player within a competent gaming experience may be enough to expose them to the principles of the science being communicated and build interest in the subject. Some games are not deemed as successful as they do not offer a ‘fun’ experience and might meet harsh criticism for not delivering on its gaming promise (Gallegos et al., 2017).

Sensationalising science:

Lastly, is the potential to communicate distorted, sensationalised science. Brown (2012) argues, the real risk of sensationalised science is not the framing itself, but the lack of critical faculties of the public to engage and evaluate the content (Brown, 2012). The extreme expressions of a public unequipped to critically engage with science are behaviours of

Scientism – uncritical semireligious perceptions of science, risking stifling the debate and promoting irrationality (Pigliucci, 2018). A such, the principles of efficient gaming education in the form of involvement of higher thinking faculties can be employed as to provide a scaffolding structure for the members of the public to practice and develop their critical thinking (Walker, 2003; Kanyapasit and Srisawasdi, 2014). A brief note must be made regarding the proliferation and spread of the fake or distorted science information. Formal logic structures can possibly be taught through gameplay mechanisms and case studies explored in some game narratives can help the public build resilience to unfounded information (Pennycook & Rand, 2021)os.

Reflection on the Arnetta's models:

In keeping with the structuralist (Robey, 1973) approach of this work, it is important to build up one's understanding and practice upon relevant theory and heuristics. Overall, the 6 "I" model by Arnetta has proven promising for delivering said heuristics for any would-be game designer. Apart from the nestled hierarchy discussed previously, the paper also presents useful list of signifiers that can be used to decide whether a game fulfil its promise as a game. These parameters are listed below and use the example of chess to show how they might apply.

Anneta'a (2010) signifiers of a game with an example of chess:

1. Feeling the activity can be successfully completed – Chess is a balanced two player game with clearly readable outcomes.
2. The player can concentrate fully on the activity, -Chess is a self-contained experience that can be resolved within its own parameters.
3. The activity has clear goals, - There are codified, standardised rules for chess.
4. The activity provides fast feedback, - The success of a player can be tracked by analysing the board layout.
5. The player is deeply involved in the activity, - Players are focused on the game itself and their interactions with and through it. Intense analytical and logical faculties are employed by the players.
6. A sense of control over the actions is necessary to perform the activity. – Game is balanced, and the conclusion is predicated upon players actions within it.
7. There is an altered sense of time. – arguable, as that would be players' internal experience. Moreover, competitive chess often involves turn counters.

Moreover, chess as a game meets the first 4 “I’s” of Arnetta’s model. As a game designed purely for the game design’s sake, chess does not meet the two outward “I’s of Informed Teaching as well as being Instructional. It does attest to specificity of the Arnetta’s framework, however, considering the reported learning benefits of chess play (Sholz et al., 2008) , a further blind spot of the model is exposed – it does not possess the non-direct and unintentional learning. It is proposed, as such with pure gaming, its previously hinted potential for providing educational benefits should be outlined and given recognition (Bart, 2014; Gallegos et al., 2017; Gobet et al., 2004; Nerueiter et al., 2020).

As it can be observed, the framework can retrospectively recognise a game and break down the elements required to fully realise a gaming project. Moreover, having said parameters pointed out helps identify areas where the game needs to improve or pinpoint where it went wrong. For example, the Dundee University Transcription Boardgame failed to provide point 6 – the game was set up to conclude eventually at its one correct arrangement eventually. Including a competitive (eg. racing) element could help mitigate that and provide better Interactivity and Identity value.

For *Belly Rumble,* the framework still applies:

1. Feeling the activity can be successfully completed – The victory conditions were achievable and players were aware of the mechanisms of achieving and declaring victory.
2. The player can concentrate fully on the activity - All resources knowledge required to engage with the game were contained within the box set. The instructions, the board and the pieces.
3. The activity has clear goals - As in point one, the first player to achieve both their randomly drawn objectives twice is declared the winner and the game stops.
4. The activity provides fast feedback - The success of a player can be tracked by analysing the board layout.
5. The player is deeply involved in the activity - After learning the rules the players were happy to engage with the game and to strategise/negotiate in a way that demonstrates understanding.
6. A sense of control over the actions is necessary to perform the activity – As above

7. There is an altered sense of time – Playthroughs lasted between 26 minutes and over 90 minutes based on the number of players but the flow of time was not apparent.

The game also is designed to provide informed teaching through ludonarrative and instruction linking to relevant literature within the subject of gut Microbiota.

There are things the 7 point model would not be able to track: the game balance needed fine-tuning and it still does at the time of writing this work. Playing with 4 players would also make the experience longer and less dynamic. Thus, the model can detect whether an activity is or is not a game but cannot point to qualities of it. Other field in which this framework falls short, is the lack of inclusion for the non-digital gaming. There is no explicit argument within the text against them, but it is an unrealised potential not to recognise that the principles of gaming seem to apply regardless of the delivery medium.

Point 7 relies on the attainment of a flow state as described in cognitive psychology (Csikszentmihalyi, 1990). Such states of perception are characterised by partial dissolution of self-awareness, feeling of competence/mastery, improved performance as well as partial obliviousness to time and the immediate environment outside of the activity. Interestingly, it also has been observed that the moment the self-awareness (identity) is restored, the flow state becomes disrupted. Arguably, the flow state exists to the state of default network (Mason et al., 2007; Buckner, Andrews-Hanna and Schacter, 2008), where the mind idly wonders as a subject "goes through the motions" of daily activity.

Flow states are rare outside of high-performing activity of a skilled subject. It is often observed that video games produce an altered sense of time, and are a highly engrossing, thus producing a flow-state when the players identity becomes temporary obliterated outside of the game (Nah et al., 2014; Murch et al., 2020) (which is also one of proposed models for developing a video game addiction). There are, however, also alternative findings with long-time video game addicts displaying a state more akin to the default network when gaming (Wan and Chiou, 2006). As argued by other paper (Kanyapasit and Srisawasdi, 2014), there are other important aspects of learners' cognition that become engaged by gaming: problem-solving and critical thinking. Moreover, while a considerable amount of scholarship explores the potential of flow-state in education (Nah et al., 2014), it is not apparent if a cognitive phenomenon so widely observed is of clear benefit to learning. Flow-states are, for example, heavily implicated in addiction to things like gaming (Wan & Chiou, 2006), gambling (Murch et al., 2020)or social media (Fox et al., 2021; Mauri et al., 2011; Nah et al., 2014). A reader, who ever experienced spending hours fully engrossed in scrolling their social media feed, may relate to the fact. Flow-states appear to be powerful cognitive phenomena, that can be harnessed for good or ill. On the other hand, it is widely argued that critical thinking and problem-solving are crucial not only to learning but also to performance in the professional world at large (Annetta, 2010; Kanyapasit and Srisawasdi, 2014). As such, we can postulate modifying the Immersion quality to be considered within the parameters of Involvement [of higher thinking faculties]. Overall, with this slight modification, Annetta's model is provably useful to a ludopedagogist in conceptualising what a game is for the sake of educational use, prioritising design elements and discussing the results.

Importance of Narrative crafting

When considering the potential of communicating complex science ethic issues through gaming two games have been mentioned. Interestingly, both the Alpha Centauri and S.O.M.A are video games and can be considered pure games. The issue of consciousness is by no way intrinsic neither to a gameplay of a 4X game (Alpha Centauri) or a survival horror (S.O.M.A). Instead, the core experience remains that of a pure game. keeping the audience captive in a state of flow; focusing their attention on the successful resolution of the game; the game narrative exposes them to ongoing debates within the science philosophy, often quoting terminology and primary sources, so one can follow up and engage a debate within the community of players (Identity/Community building principle). Exercises in cooperative storytelling like LARPs and storytelling games (eg. DnD) can be used to incorporate mature philosophical themes. These in turn can be explored within the simulated/imagined reality without the adversarial character of an open academic debate.

Interestingly, in adult population, psychological indicators between different gaming mediums, indicated that content is less appealing than the interaction itself – to summarise the experience of the game seems to matter more in the test subjects (Marston, 2013). Perversely, it should be considered an opportunity, as it indicates the pure gaming experience may be able to keep the player entertained for long enough to explore some more challenging science material. Narratives present themselves as a very powerful tool in the science communicator's toolkit. Games like Senua's Sacrifice, the Darkest Dungeon, Alpha Centauri or S.O.M.A, stripped of their narrative content, become common representatives of their respective genres. Again, the gaming element carries the narrative content. The game can be used to expose the player to the material they did not explicitly come to seek out, that may be outside of their comfort zone or intellectual awareness at the time (Gowler & Iacovides, 2019). It is explicitly a manipulation technique, one can use to any end – be it positive or nefarious (Kikkawa, 2022).

Conclusion:

Despite modern preconceptions, gaming is not a new phenomenon. The understanding of what makes play and how to partake in it seems to be hardwired into not only humans but even other higher animals. The digital medium has merely served to elevate the complexity and marketability of gaming. As such, even as science communication practitioners we are intrinsically equipped with a working understanding of how to make a game no less than the target audience is primed with motivation and understanding on how to play it.

In the spirit of transdisciplinary cooperation (Nicolescu, 2014), the medium of game development may become a "third space" in which scientists, artists and game designers may meet to bridge divides within the body of epistemological knowledge as well as push further our cultural understanding and participation within arts and sciences. The syncretic nature of game design opens itself up to large collaborative projects, where game designers, artists and science communicators contribute uniquely and valuably through their available tools – both ludic and non-ludic. While the authors believe that the narrative exposure may be the single most powerful tool in a ludopedagogical approach, it cannot fully manifest without engaging gameplay design and becomes purposeless or harmful bereft of sound scientific content.

This chapter serves three main purposes: it is a primer on use of games in scientific communication aimed at those considering such approach in their practice; it facilitates through practical distinction between the pure and serious gaming as well as the digital and the traditional media, and it assesses and balances their potential and difficulties for the reader to better inform their approach. Many projects exist in isolation partly because of lack of dialogue between the different specialists. As such, dialogue must be built and maintained to facilitate change. Lastly, this chapter is a call to action – ludic approaches can be used to effectively promote science, improving the quality of learning, and aid in scientific information transfer, however, the potential is still mostly unrealised and that is good news for prospective serious game designers.

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