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# From crossing chromosomes to crossing curricula – a biomimetic analogy for cross-disciplinary engineering curriculum planning

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## ABSTRACT

Interdisciplinary engineering programs have many perceived benefits including developing broader skills and an ability to work with complex real-life problems. However, the development of interdisciplinary programs faces many challenges including how to balance breadth and depth, how to integrate interdisciplinary learning into existing studies and how to work across university structures. In the development work and in communicating interdisciplinarity, T-, Y- and Pi-shaped visualisations are often used. We develop an improved model by using biomimetic analogy from genetics to aid in interdisciplinary curriculum planning. We map analogies between how genes and chromosomes act in the evolution of species and how similar mechanisms can aid in evolving curricula. We identify three genetic mechanisms to include interdisciplinarity in the curriculum: mutations as unplanned changes, DNA inserts as modular curriculum structures, and crossing chromosomes as cross-disciplinary programs. We use examples from two universities to detail how this analogy helps to reframe curriculum planning.

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Analogue; analogical mapping; engineering education; curriculum; interdisciplinary; biomimetic

## 1. Introduction

Academic degrees, programs, and curricula have evolved throughout the existence of the university institute. In today's changing world, universities are struggling with maintaining the value of higher education, which is built into the current degrees over hundreds of years. In the early years, engineering consisted of only a few disciplines, such as civil and mechanical engineering. Since then it has branched out to many other disciplines, including the relatively recent fields of bioengineering and information systems. In addition to the new disciplines, it is recognised that for engineers to solve complex problems, new skills and a more interdisciplinary education is needed. The quote 'We are currently preparing students for jobs that don't yet exist, using technologies that haven't been invented, in order to solve problems we don't even know are problems yet' (Gunderson, Roberts, and Scanland 2004) is truer than ever.

To tackle this challenge, the introduction of new, increasingly more specialised degrees is not necessarily a feasible solution. Universities can also increase diversity by enhancing interactions between the existing disciplinary degrees. We have seen mergers of universities that traditionally represented different disciplines and newly established universities that emphasise their enhanced possibilities for crossing disciplines within a degree. Examples of the former

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include the multidisciplinary Aalto University in Finland, that was founded ca. 10 years ago as a merger of three universities: Helsinki University of Technology, Helsinki University of Economics and University of Arts and Design; and the 2019 merger of the universities Paris Diderot, Paris Descartes and Institut de physique du globe de Paris into a single multidisciplinary University of Paris. Two examples of the latter type are the Olin College (2002) and Singapore University of Technology and Design (SUTD 2012), which were established as interdisciplinary from their onset.

This increase in diversity in competencies should not degrade the competencies or the value of the traditional engineering degrees. The question here then becomes, how to maintain the competence and value and yet evolve simultaneously and effectively. Universities are not alone with this evolutionary dilemma. Ultimately, all ecosystems, including nature and all the species in it share the same struggle. Each species strives to continue its existence as a species and to simultaneously change to be able to adapt to new conditions. Strikingly, the mechanisms enabling this originated millions of years ago and they are still the state-of-the-art tools for evolving. The similarity between diversity in the ecosystem and diversity in the universities hints at an opportunity to use them as analogues, to use one to inform the other. In this paper, we present a novel conceptual model to re-represent interdisciplinary curriculum planning by using analogical mapping from genetics to curriculum design.

## 2. Approach

Analogical thinking is a powerful tool used in the past by scientists (Gentner and Smith 2012) and designers (Casakin and Goldschmidt 1999) to advance the field or solve problems by seeing it from a different perspective. An analogue can help recognise and reason about commonalities across different domains (Gentner and Smith 2012). This is called analogical mapping. In that, a base analogue is used as a source to derive new insights into a target analogue. At best, an analogue can help draw predictions and explain the target situation in a novel and useful way (Gentner and Smith 2012). Gentner and Smith (2012) further argue that analogues can help knowledge building in at least three ways by abstraction, difference detection, and re-representation.

To this end, we propose a novel analogue from genetics to help reframe, re-represent, and support adding disciplinary diversity in engineering curriculum. Genome adaptation plays a key role in helping the ecosystem adapt and increase diversity. Could this analogy be useful for interdisciplinary curriculum design? What can be learnt from the genome and its functions that could be useful in how to design education? Could we find useful analogies for evolution of education and adaptation of academic institutions from the mechanisms behind evolution of cells and the tools of recombinant DNA technologies?

For us to do this successfully, we first establish clear relations between the base analogue of genetics and target analogue of engineering curriculum. We follow the multiconstraint view of Holyoak and Thagard (1997) by aiming for analogues that have a useful degree of similarity, structure, and purpose. From design and engineering design, we know that analogues are useful for problem-solving (Casakin and Goldschmidt 1999), they can help with fixation and cross-domain knowledge transfer and it has been shown that far-field analogies might be more useful than near field analogies (Fu et al. 2014). We present the genome as a useful far-field analogue for interdisciplinary curriculum design.

Following the analogical mapping approach in this paper we will (i) map the genetic mechanisms that enable the development of new properties and combinations with the actions taken when developing new engineering curricula, and (ii) discuss how the genetic mechanisms could reveal new perspectives and factors for engineering curriculum planning. We will use real university curricula as examples to present the analogy and its usefulness in curriculum planning.

### 3. Relation to past work

In this paper, we present a bioinspired analogue to support interdisciplinary curriculum development. In the past, few other curriculum level models have been introduced. For example, Rompelman and De Graaff (2006) use a design process analogy for curriculum design, where students are the input in the process, education is the design process, and outputs are the graduates. Fleischmann and Hutchison (2012), on the other hand, present a POOL model where they can pool student and faculty resources as needed for interdisciplinary projects. This model is meant for managing resources in an interdisciplinary environment where one faculty is needed in more than one course or project, but perhaps only partially. While not directly using the POOL model, a similar approach to dividing students and faculty into cohorts from a pool can be seen in an interdisciplinary capstone program (Magnanti and Natarajan 2018; Sng et al. 2016). Rikakis, Tinapple, and Olson (2013) present a model to balance the breadth and depth in the curriculum that merges two disciplines (engineering and arts). They discuss how a competence-based model is used to supplement a more traditional knowledge-oriented education in the integrative studies that are targeted to train good ‘engineer-artists’. Other approaches include integrating Problem Based Learning (Mitchell et al. 2019) and other active learning-based approaches (De Graaff and Ravesteijn 2001) in the curriculum and using percentages for required interdisciplinary, integrative or other requirements (Madden et al. 2013).

#### 3.1. *Disciplinary and narrow vs. broadening skills*

Multi-, inter-, cross-, and other forms of disciplinary are often used interchangeably, and there are no commonly agreed-upon definitions. Most commonly, multidisciplinary refers to the simplest form of collaboration between disciplines and the other forms refer to a more integrated or co-dependent forms (Knight et al. 2013). For example, Choi and Pak (2006) write that multidisciplinary work draws knowledge from different disciplines, but the disciplines stay separate, whereas interdisciplinary work is a more coordinated effort. In this paper, we discuss curriculum efforts to accomplish multi-, inter-, trains-, and cross-disciplinary programs. For the sake of simplicity, we will use the term interdisciplinary from now on.

A common agreement is that there is inherently something positive about interdisciplinarity (Petrişor 2013). Interdisciplinary studies are usually aimed to increase either (1) broader interdisciplinary skills, or (2) they aim to teach the students skills from more than one discipline. The broader skills are meant to broaden the potentially narrow view of a student studying any specified field (Marques 2008). These broader skills usually include teamwork, communication, awareness of other approaches, or linking information from one field to another (Borrego, Newswander, and McNair 2007; Borrego and Newswander 2010; Lattuca et al. 2017). The broader skilled individuals are often referred to as T-shaped individuals. Bierema (2019) discusses how the idea developed and was popularised in the 1990s. The idea was to have a broader T-bar to balance the I-shape, or the narrow but in-depth studies from one field. Since then also other shapes have been discussed. Some of the shapes, such as Pi- and Y-shapes include deeper knowledge from two fields (Demirkan and Spohrer 2018), which is in line with the second common goal of interdisciplinary studies, developing skills in more than one discipline. Further, an interdisciplinary approach is highlighted in today’s wicked problems, specifically in the field of global sustainability challenges (Ashford 2004; Segalàs Coral and Tejedor Papell 2013).

#### 3.2. *Interdisciplinary programs*

Given the assumed benefits of interdisciplinarity, many programs and courses have been created over the past decades. Ruano-Borbalan (2019) discusses the history of the development of interdisciplinary innovation programs. They date back to 1980s and 1990s and grew increasingly common in

2000–2010s. For example, a Product Development (PD) project course at Aalto University, offered to students from engineering, business and arts just celebrated its 20th anniversary. Similarly, Aalto University multidisciplinary program between business, industrial design and engineering began over 20 years ago. Miller and Olds (1994) describe a multidisciplinary capstone already in the 1990s. Some examples of interdisciplinary programs or courses include service-learning projects (Davis et al. 2014; White and Nitkin 2014), a common studio (Cotantino et al. 2010), or a course (Deo, Hölttä-Otto, and Filz 2020; Keenahan and McCrum 2020; Li et al. 2015) between architects and engineers; and mechatronics courses offered for both mechanical and electrical engineering students (Arkin et al. 1997; Shooter and McNeill 2002). Spitzer (2013) discusses two case studies of integrating interdisciplinary teaching into the curriculum in Turkey and Germany.

In engineering, a multidisciplinary capstone course and cornerstone projects are common (Dym et al. 2005). Goldberg et al. (2014) discuss one of the reasons for this, industry collaboration. However, a typical capstone course is still only a course, or a two-course sequence. According to a study by Richter and Paretto (2009), 60% of academic multi- and interdisciplinary research projects were projects or courses and 38% were larger efforts – 23% curriculum level and 15% institutional level efforts. The remaining 2% were something else such as change in assessment. Overall interdisciplinary content can take many forms and can be as short as a one session or one week-long design project that merges more than one discipline, a Designette (Telenko et al. 2016), or can span multiple terms or semesters (Conger et al. 2010).

### **3.3. Benefits of interdisciplinary education**

There are many reported or expected benefits from interdisciplinary education. The benefits vary depending on the timing and type of multidisciplinary course or program. For example, a first-year interdisciplinary course was shown to help in retention (Froyd and Ohland 2005) and a similar program helped in attracting underrepresented groups to engineering (Davis et al. 2014). Later programs, such as capstone programs, are more likely to target skills related to e.g. working in multidisciplinary teams and ability to solve complex real-world problems (Miller and Olds 1994). Hotaling et al. (2012) show students from multidisciplinary projects outperformed their mono-disciplinary counterparts in project performance and employability.

Some interdisciplinary courses and programs are designed to increase specific skills such as creativity (Cotantino et al. 2010; Deo, Hölttä-Otto, and Filz 2020), broader work life skills (Costa et al. 2019; McKay, De Pennington, and Giard 2013; Steiner 2004; Tranquillo 2017), or specific multidisciplinary skills such as ability to ‘synthesize both concepts and approaches from multiple domains to develop an integrated solution to a given interdisciplinary challenge’ (Lattuca et al. 2017; Richter and Paretto 2009). On the other hand, programs that merge (usually) two disciplines often aim in equipping students with skills from more than one disciplines thus producing ‘bilingual’ students (Bierema 2019; Klaassen 2018). Other reported benefits include faculty development (Froyd and Ohland 2005).

Given the desired benefits of the different types of interdisciplinary programs, there is a need to better understand how to integrate those into a curriculum.

### **3.4. Barriers and challenges in developing interdisciplinary curricula**

While the broader skills are a common desired outcome and benefit in interdisciplinary education, there is a tradeoff between depth and breadth in the curriculum (Borrego and Newswander 2010). Merging ideas from many disciplines cannot add to the overall credits in the curriculum. Bovill and Woolmer (2019) discuss the common pressure to try to fit too much into the curriculum. What is considered foundational may need to be reconsidered in interdisciplinary curriculum design. Further, Sinnema and Stoll (2020) discuss the interrelated challenges of balancing depth and breadth, and the related reach and pace, in curriculum planning:

Each new curriculum idea or element demands depth of understanding of those with any responsibility for realising curriculum or supporting this. For each element, understanding is required about the: theories underpinning it; rationale for its inclusion; key concepts associated with it [etc.]

Curriculum planning is challenging even in a single discipline, but when working with topics from outside one's expertise it becomes even more difficult, especially if the disciplinary distance (Feng and Hölttä-Otto 2021; Kelly 1996) is great. This means the process becomes dynamic and all parties learn more as the process goes along whether it is a course (Li et al. 2015) or curriculum scale effort (Clark et al. 2004; Borrego and Cutler 2010). It is recommended that faculty members define clear learning outcomes and align curriculum expectations to help with the situation (Borrego and Newswander 2010; Sinnema and Stoll 2020). On a curriculum level, Van der Hulst and Jansen (2002) argue for proper curriculum organisation. They find it is needed to support student progression their studies.

Another common challenge is to integrate the interdisciplinary learning into other studies. Richter and Paretto (2009) report how students failed to link the knowledge from an interdisciplinary sustainable engineering program to their own studies and how they failed to see the value the other disciplines brought to the program. Rikakis, Tinapple, and Olson (2013) discuss the same problem in knowledge-based education combining two disciplines.

Interdisciplinary efforts also face barriers due to the nature of the efforts, namely involving more than one discipline and thus often acting outside typical academic disciplines, structures and e.g. tenure processes (Roth and Elrod 2015). Ruano-Borbalan (2019) discusses how disciplinary realities and power struggles lead to fragmentation of interdisciplinary efforts. Froyd and Ohland (2005) mention administrative challenges as one reason interdisciplinary curriculum pilots do not stick. Ashford (2004) adds how tenure track faculty may take too large of a risk if they step outside their field as the faculty recognition is often within disciplines.

Given the wide set of challenges, past research has also offered tips on how to address these. These include e.g. use of design projects that help students make connections between subjects (Froyd and Ohland 2005). Telenko et al. (2016) describe short Designettes as one form of such interdisciplinary design projects. Roth and Elrod (2015) list several recommendations to tackle many of the challenges including developing co-teaching models and a course scheduling mechanism to take down practical barriers preventing faculty from different disciplines from working together. Bierema (2019) also advocates for team teaching. Roth and Elrod (2015) suggest integrating multidisciplinary in the tenure criteria and potential use of memoranda of understanding to clarify roles and responsibilities in case of multi-department review, for example. They also highlight the need to integrate the new interdisciplinary effort in the current offerings rather than adding new programs. This could be facilitated by building joint spaces and other resources, including budget. Finally, they highlight the importance of both internal and external communication about the interdisciplinary programs.

We aim to address a few of the above challenges. Namely, we wish to provide help in balancing breadth and depth in the curriculum. We wish to provide mechanisms to integrate the interdisciplinary component into the other studies as well as ways to solve the problem of overstuffing the curriculum when merging studies from more than one field together. We hope our model serves as a tool to facilitate the discussions on these topics between different disciplines.

#### 4. Background and terms used

Before making the analogy from genes to curriculum planning, we will first introduce the relevant genetic terminology. Genetics include the central information on a specie in the same way as a curriculum includes intended competencies for graduates. Both; genetics and curricula have potential for variation within a specie or between the competencies of individual graduates. Furthermore, they both have capability for evolving and potential for producing new combinations. Mapping the structures and mechanisms behind the similarities, is the first step in our analogy development.

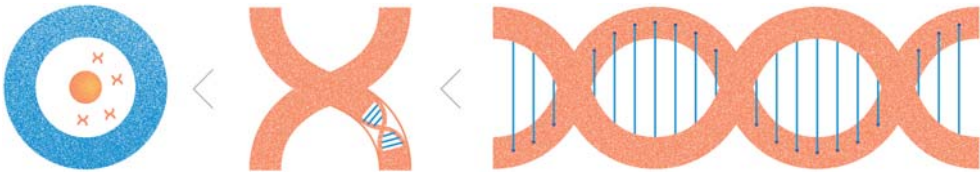
#### 4.1. Genetic material and mechanisms

The cell is a unit in which all the genetic material exists, and in which all genetic activities take place. The central information for the reproduction of a cell is in the chromosomes; the double-stranded structures of the DNA (Figure 1). More specifically, the information in the DNA is carried in genes – functional snippets of DNA each of which has a defined function to code. In human chromosomes, there is also DNA outside of the genes, which is called non-coding DNA. The exact role and function of the non-coding DNA is not known.

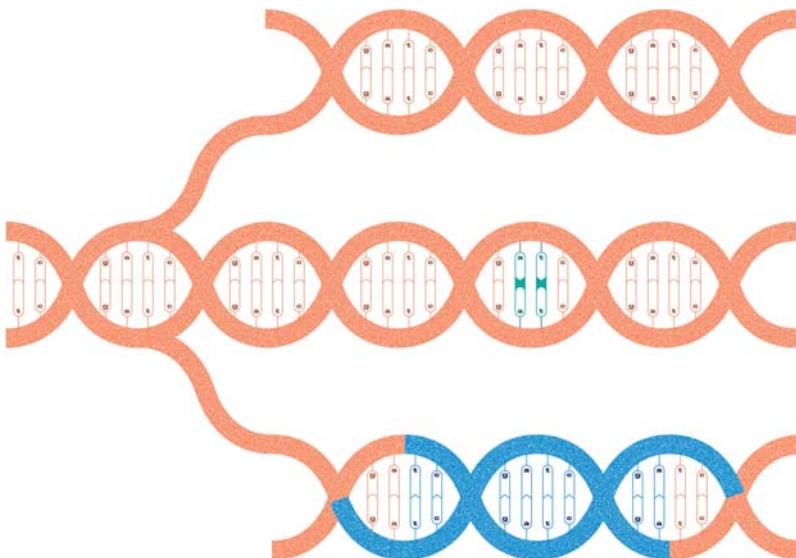
#### 4.2. Genetic code and its modifications

DNA is a self-copying double strand of nucleotides with four different bases: Adenine (A), Thymine (T), Guanine (G), and Cytosine (C). The strands link to each other by the connection between base pairs: A with T, G with C. This four-digit code forms the very core of genetics (Figure 2). However, the key to survival is the ability to adapt. The mechanisms related to producing variation are related to the regeneration. There are basically two types of reproduction: an asexual and a sexual one. In the former, the basic situation is that the DNA copies itself and the modifications are occasional; based on mutations, while in the sexual reproduction the parent DNAs merge and form modifications of themselves in the offspring.

Mutations are random errors in copying during DNA duplication. They may take place in either form of the reproduction. The error may be a result of a mismatch between the bases. For instance,



**Figure 1.** Genome basic structures: Cell, chromosome and DNA double strand.



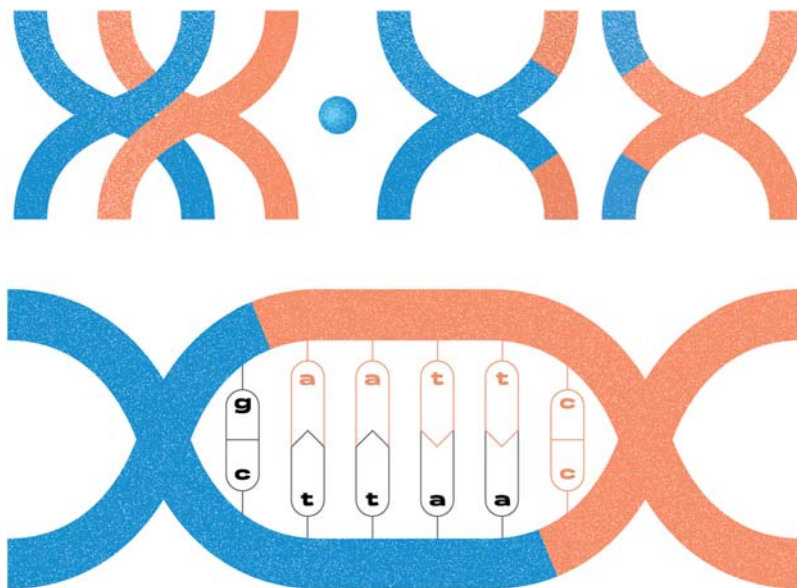
**Figure 2.** DNA replication (top), mutation in base pairs (middle) and by a foreign DNA insert (below).

T replaces C as a counterpart of G, which leads to formation of a mutant DNA (Figure 4). A mutation may also delete a piece of the DNA or duplicate it. Errors in copying may be induced, for instance, by certain chemicals and radiation.

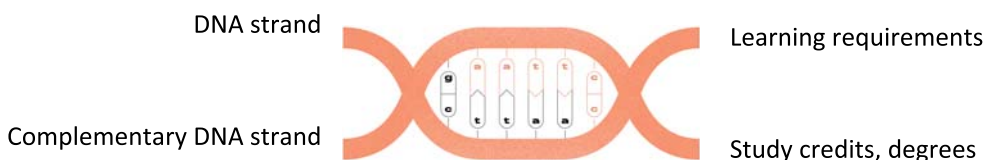
There are different mechanisms by which pieces of DNA may be integrated into the chromosomal DNA – for example injection of viral DNA and crossing over of chromosomes. At the DNA level, the action of viruses resembles genetic engineering as in both cases, the target DNA strand is cut in a spot with the right code of bases and the new piece of genetic code is integrated into the original strand. The result in both is recombined DNA in which the insert is integrated as part (Figure 2).

Recombined chromosomes are also formed spontaneously, when DNA strands of resembling chromosomes cross-over each other and exchange pieces of the strand between the parent chromosomes. This form of DNA modification takes place in sexual reproduction. This will result in formation of new recombined chromosomes with new combinations of genes (Figure 3). The recombining chromosomes must be equal by the size and by the function. In other words, the genes of the recombining chromosomes must code the same function and be located at the same positions in the chromosomes.

The joined DNA strands in the cases of DNA insertion and recombination are formed between compatible base sequences between the two DNA strands (Figure 3). Similarly, the compatibility between the joined DNA strands is necessary regardless of inserting viral DNA, DNA strand in genetic engineering or in the spontaneous formation of recombined chromosome.



**Figure 3.** Formation of recombined chromosomes by crossing over (top). Detail of a joint in a new merged DNA strand (below).



**Figure 4.** Complementary double structure in DNA and in university teaching.



## 5. Genetics inspired interdisciplinary curriculum design

In order for an analogical mapping to work, we need to establish a clear mapping for both the elements and their structural relations in the analogy and demonstrate the usefulness (Gentner and Smith 2012). Thus, we build our genetics-inspired conceptual model for interdisciplinary curriculum design in stages. First, we seek analogies between the elements and structures of university education and the elements and structures in the genome. Second, we map analogies in mechanisms that increase variation in universities and in the arrangement of genes, or their combinations. We perform a conceptual exercise by taking examples from multiple different interdisciplinary programs from two universities known for their interdisciplinary efforts. Aalto University is a recent merger of universities, representing a case where existing established curricula need to be redesigned. Singapore University of Technology and Design is a new university with no pre-existing curricula. Third, we assess the opportunities and limitations associated with the genetic mechanisms for increasing diversity in a chromosome. These pros and cons are then reflected upon in the context of increasing diversity in a university curriculum. Finally, we bring the learning into a form of guidelines for building interdisciplinarity in the curriculum.

### 5.1. Mapping between genetic and university education structures

The entity in which all the education and its development takes place is the University. The evident counterpart for this is a Cell in which all the genetic material exists and where all the genetic activities take place.

Chromosomes have defined length and number of genes in them in the same way as any curricula has a fixed number of study credits and courses in it. Consequently, the courses map with genes and a curriculum with a chromosome. Typically, the courses are either mandatory or elective. The elective courses can be chosen from a list of courses or they can be free electives. The free electives differ from the mandatory and elective courses by their nature. There is no specified learning goal for a free elective course in the curriculum – rather a space and a request to extend academic studies in any field. Specifically, from the interdisciplinarity increasing point of view, the free electives may be equally chosen from one's own or from another field. Instead, the electives aim at learning at a more specific thematic field, such as general education electives or humanities and social sciences courses for engineers. The courses with mandatory or elective nature in the curriculum have specific roles and positions in the learning. The evident match for the defined roles in genetics is the DNA packed in genes. From this follows that the non-coding DNA is left for the free electives. This is a logical mapping as in both cases, we do not define specific learning goal of a general free elective course i.e. and yet, we need to have a certain amount of them.

Regardless of the type of course, the courses have defined learning goals and defined study credits as the recognition of learning. Here, between learning goals and learning recognition, we recognise a complementary double structure built on matching counterparts. This equals to the complementary strands of DNA (Figure 4). The same double structure extends to the chromosome i.e. curriculum level, where universities define the learning requirements and entitle degree for executing these.

In sum, we were able to map each part of a genome into the university structures (Table 1). Below we use these analogies to create variation, specifically add interdisciplinarity, in the curriculum.

### 5.2. Mapping mechanisms for creating variation

The changes in a curriculum may stem from an individual student, they might be additions to an existing curriculum, or they might be more significant restructuring efforts. We map these approaches to the described mechanisms for chromosome variation: mutation, inserting strands of DNA, and crossing over chromosomes.

**Table 1.** Mapping of genetic structures to university structures.

Structure in genetics	Analogue in University education	Common properties
Cell	University	Entity in which all structures exist
Chromosomes	Curriculum	A defined entity of intended properties
Gene	Mandatory course	Unit with a defined function
Non-coding DNA	Free elective courses	Structures with non-specified functions
• Base sequence in DNA single strand	• Learning goals	Double structure of complementary parts
• Base sequence of counterpart of DNA single strand	• Study credits, degree	

### 5.2.1. Student-driven changes in curriculum as spontaneous mutations

Small spontaneous changes in a curriculum take place when students suggest an alternative way as a (partial) replacement of the courses in their curriculum. These alternatives may originate, for instance, from exchanges studies or a summer school. The common factor in all these is that they represent non-standard learning experiences. In our analogy, these resemble mutations.

The requests may be in the form of recognition for prior learning (RPL) from working in a student organisation or extracurricular, e.g. entrepreneurship activities. In these cases, students consider that they have learned essential competences and request possibilities for getting these competences recognised as study credits. In our genetic analogue, this resembles to fitting an unintended base (s) in the DNA strand. The mutations as well as course alternatives initiate randomly, and they may be one-time only or they may become a new additional alternative into learning goals of obligatory courses. As an example, at Aalto University, there are some high-profile extracurricular entrepreneurial activities that take significant time. Generally, they are seen as valuable and supported by the university, but they are not part of any curriculum. These ‘mutations’ are now being integrated into the actual curriculum by developing learning outcomes and associated tasks to turn the activities into recognised learning experiences.

### 5.2.2. University driven inclusions in studies as formation of recombined chromosomes by DNA inserts

Interdisciplinarity can be integrated into the curriculum in many ways. In our case university, Aalto University, disciplinary diversity is driven by the original goal of the merged university to bring different disciplines together. During the first years, different approaches have been implemented. The course-sized and program level attempts we identify at Aalto University can be divided into (i) free-elective studies, (ii) mandatory interdisciplinary courses, and (iii) restricted electives. The restrictive electives are electives from a predefined list of courses, not fully free electives. In addition to if the courses are mandatory or not, we find the interdisciplinarity is included in three distinct ways: by (i) requiring students to take course from a discipline outside their own, (ii) by offering interdisciplinary courses, and (iii) by opening own regular courses to students from also other disciplines. We can map example courses designed to increase disciplinary diversity in Aalto University in a matrix (Table 2).

Free electives do not specifically build interdisciplinarity in a university as this alternative exists in any curriculum and students are equally free to not select them. What was specific in the case of increasing interdisciplinarity in Aalto University, was a novel offering of design and arts studies for non-arts students (UWAS, University Wide Art Studies). Similar to University wide art studies, also Business and Technology studies are offered to students outside those specific fields. In our analogue, these efforts for increasing interdisciplinarity match inserting non-coding DNA. On one hand, there are no restrictions for the offering of free electives, which make the implementation easy. On the other hand, the exact impact of the non-coding DNA remains uncertain. This maps well with the impact of free electives as a tool for increasing interdisciplinarity as the student can choose free electives from their own field. In addition to the previous single course inserts, minor

**Table 2.** Courses at Aalto University that aim to increase interdisciplinarity categorised by the degree of selectiveness or type of disciplinary offering.

	Free electives	Restricted electives	Mandatory
Other	University wide art studies University wide business studies University wide tech studies		
Interdisciplinary	Interdiscip. Project Course <i>P</i> Interdiscip. Project Course <i>M</i> Interdiscip. Minor on Product Dev		Interdiscip. Project Courses <i>S</i> & <i>E</i>
Own to others	Minors	Selected University courses	

studies are a common way to enable interdisciplinarity in a curriculum. A minor from another field or an interdisciplinary minor enables combining a new discipline in one's own. Like an elective course, an elective minor is also only non-coding DNA and while beneficial, the exact impact remains unclear.

Aalto University also introduced mandatory interdisciplinary project courses (*S* & *E*) among the basic studies during the renewal of the entire degree programs. The courses are introductory project-based courses where students work together with students from other disciplines and thus give a glimpse into interdisciplinary collaboration. These mandatory interdisciplinary courses are analogous to genes. Regardless of the nature of a mandatory interdisciplinary course, it always calls for a choice between the new interdisciplinary course and some other, possibly field-specific course, among the restricted space of the mandatory courses. Restricted electives fall between the free electives and mandatory courses. In Aalto University, a list of elective courses from different disciplines were introduced as a mandatory part of the curriculum for all the students. However, the original idea of making students to cross disciplines met obstacles. Namely, the schools were able to independently define the course list that they offer for the students from the other schools, and the courses from other and own school for their own students. Consequently, the content varied from school to school and included courses in own discipline as well as in others. Hence, the single combining learning goal between the university wide electives; to encourage the students to cross the disciplines, was not necessarily met. This approach seems to combine the negative parts of the both previous approaches: the effort to make space in a curriculum, which results in an undefined goal in terms of increasing interdisciplinarity. In our analogue this, maps with gene due to its mandatory status, but from the content point of view, it remains close to non-coding DNA with no exact specified function.

Besides the above examples, [Table 2](#) offers an interesting insight. We observe that we can find several courses in the Elective category and less in the other categories. This is natural since free electives do not require significant integration into formal curricula. But since they then remain only non-coding DNA, their impact in increasing interdisciplinarity, as mentioned earlier, remains unclear.

For these DNA inserts, or course inserts in the curriculum, to fit well, the joints between the DNA double strands and introduced genes need to match with each other by base pairing. Similarly, the mating parts of the course prerequisites and the possibility to achieve the course learning outcomes must match. The prerequisites for a course or a minor can be defined either according to recognised learning i.e. completed courses or as specified learning requirements. When defining the prerequisites according to completed courses, the threshold for taking the minor comprises scheduling according to the required course. Moreover, the course often contains other elements than the ones that are needed for successful studies in the minor. Instead, when the prerequisites are defined according to the essential elements that are needed during the minor studies, a motivated student may study those elements independently, or various bridging course modules could be offered. In practice, the prerequisites should be expressed specifically e.g. 'ability to write basic C + code and understanding principles of programming' rather than 'Course CS101-Basics of Programming'.

### 5.2.3. Merging curricula as formation of recombined chromosomes by crossing over

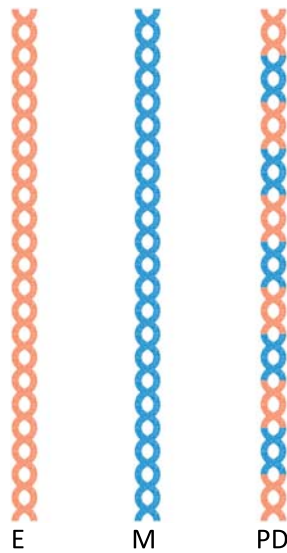
There are more extensive ways for increasing interdisciplinary. Instead of simply adding or replacing studies, a fully interdisciplinary program could be created by integrating elements from different disciplines. In our genetic analogue, these integrations take place when the chromosomes recombine by crossing over. The chromosomes need to be the same length as is the case with the merging curricula. Furthermore, the genes in the strands that cross-over need to match the position in the same way as the courses in the curricula need to match their position or level. Our curriculum development example is from SUTD. There, rather than having traditional Mechanical (M) and electrical (E) engineering curricula, SUTD merged the two into a combined PD curriculum. Eleven out of 20 courses were already originally the same since the university was newly designed to be relatively interdisciplinary. Fitting the differing courses as one curriculum was achieved combining different approaches that we will discuss below (Table 3).

There are no exact mappings for the alternative choices on the courses (Table 3) in genetics, where only one gene of each of the merged DNA strands can remain in the newly formed chromosome. However, we find analogies between the equally sized chromosome strands, which are crossing over: The joints between the DNA strands must fit each other and the new recombined chromosome must remain the same length and in the same location as the original ones (Figure 5). In the case of curriculum merger, we detect the following ways of using the existing courses of the original curricula in the new curriculum:

- (1) Mandatory courses from both disciplines remain mandatory (Circuits and electronics AND Structures and materials)
- (2) Mandatory courses become alternative choices (Fluids Mechanics OR Electromagnetism)
- (3) Mandatory courses are merged and the new merger course is kept mandatory (Signals and Systems & Feedback and Controls merged as Signals and Controls)
- (4) Mandatory courses are included in a common pool of elective courses (Thermal Systems for Power and Environment, Microelectronic circuits and devices, Dynamics, Design and fabrication of MEMS, and Digital Systems Laboratory into PD Electives)

**Table 3.** The courses from the two curricula were merged into a single curriculum. 11 courses were the same from the beginning and they were kept the same, the others needed actions to be able to for combined curriculum.

Mechanical (M)	Electrical (E)	PD	Actions for forming combined PD curriculum
Probability and Statistics	Probability and Statistics	Probability and Statistics	–
Signals and Systems*	Signals and Systems*	Circuits and electronics	Signals and systems merged with Feedback and control into Signals and control (in addition a new advanced feedback and control course was included as an elective) Circuits and electronics defined as mandatory
Structures and Materials	Circuits and electronics	Structures and Materials	Structures and materials defined as mandatory
Feedback and Control*	Feedback and Control*	Signals and Control*	Feedback and control was merged with Signals and systems and the new course: Signals and control, which was defined as mandatory
Eng Design & Project Eng	Eng Design & Project Eng	Eng Design & Project Eng	–
Fluid Mechanics	Electromagn & apps	Fluid Mechanics OR, Electromagn & apps	Fluid mechanics and Electromagn. & apps were defined optional choices
Thermal Syst for Power and Env Dynamics	Microelec circuits and devices	PD Elective	The courses from E and M were chosen to common PD elective list
	Design and fabric of MEMS	PD Elective	
M Elective	Digital Systems Lab	PD Elective	
2 M Elective	2 E Elective	PD Elective	E and M elective lists combined as common PD elective list
5 HASS	5 HASS	5 HASS	–
2 Tech Electives	2 Tech Electives	2 Tech Electives	–
Capstones 1&2	Capstone 1&2	Capstone 1&2	–



**Figure 5.** Visualisation of recombined chromosome analogue of merging of Electrical (E) and Mechanical (M) engineering curricula into PD curriculum.

The example from SUTD is for an entire program. The same process can also be done for shorter sequences e.g. interdisciplinary tracks between programs. In fact, this was done in SUTD. The logic and mapping into our genetic analogue is the same as for the presented example and thus the example is not further elaborated here.

When viewing the different kinds of choices (1–4 above) for using the existing courses in the new curriculum we recognise that the most common way is to include a course to the list of elective courses offered in the curriculum.

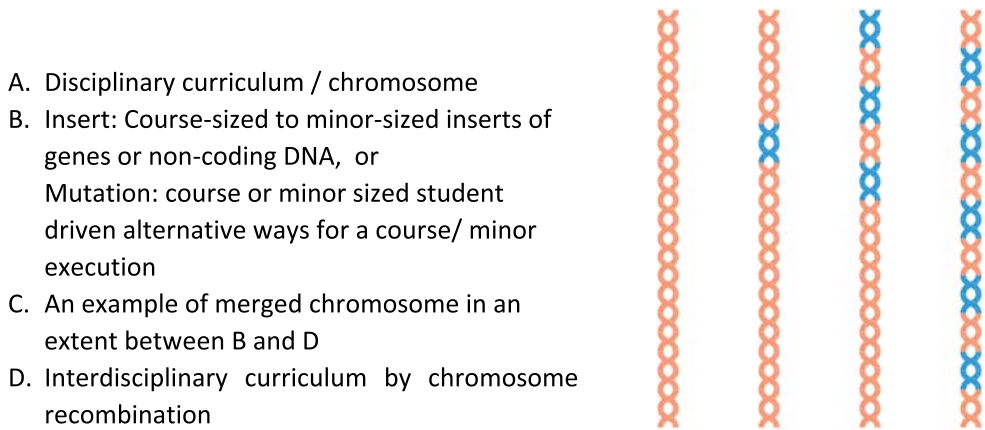
Whether designing one or more interdisciplinary curricula, our analogy suggests several useful guidelines. First, the matching joints resemble to detailed definition of prerequisites as was discussed in the case inserts above. Still, in the case of merger including several joints, this factor becomes crucial. Second, as mentioned earlier, the new merged curriculum cannot exceed the size of the original curricula, which highlights the need for making choices between the existing courses must be made. Third, the genes or courses must maintain their position or level so that the new curriculum does not sacrifice the depth in substance learning.

## 6. Discussion

Our aim was to develop a novel model to help reframe interdisciplinary curriculum planning and support increasing diversity in disciplinary studies. Our analogy aims at bringing a novel neutral view into the negotiations between several disciplines on the choices to be made when building study structures towards greater interdisciplinarity. In this section, we discuss the results of our analogical mapping, its possibilities and limitations in interdisciplinary curriculum planning as well as how the model can be used as a tool to facilitate discussions between disciplines.

### 6.1. Analogical mapping

We mapped analogies between the genetic structures and the elements in the university education; and the mechanisms for creating diversity in genetics and in curricula. The mapping between the structures; cell, chromosome, DNA double strand with genes, and non-coding DNA resulted in a



**Figure 6.** Bioinspired tool for increasing interdisciplinarity in a disciplinary curriculum.

coherent analogy with a university, a curriculum, learning goals and learning recognition, mandatory, and free-elective courses, respectively. The structural mapping enabled us to map the mechanisms for introducing more diversity from genetics to curriculum planning. The successful mapping helped identify mechanisms for diversity while maintaining the essential nature of the specie or the disciplinary expertise built into a degree.

We discussed different ways of introducing new elements in a curriculum: mutations, DNA-inserts, and recombining entire chromosomes. We found matches to these as follows: student-driven alternative ways of executing a course (or part of it) or a program, course- and minor-sized inclusions, and a forming of a new curriculum out of two (or more) original curricula. As a result of these actions, different levels of recombined curriculum may be achieved: (1) course or minor sized mutations or inserts of gene or non-coding DNA, and (2) interdisciplinary program or track. These different extents of interdisciplinarity are visualised in Figure 6. Evidently, the extent of merging may vary between these.

## 6.2. Possibilities and limitations of the analogy

When analysing the outcomes of the mapping between the mechanisms, we found possibilities and restrictions in each and were able to highlight certain repeating conditions for successful evolution (Table 4).

First, mutations or student-driven alternative ways for course execution take place spontaneously. Like in nature, mutations can be negative, even defects, but also positive and lead to novel evolutionary directions. Recognising this potential from our analogue can help harness the potential of positive mutations. The student proposals for the alternative ways may be dealt case-by-case by various decision-makers from a teacher of a course or coordinator of internships. To effectively utilise the student-driven alternatives for increasing diversity, a transparent and uniform RPL process for assessing the learning from extracurricular activities should be established at the university level.

The second analogy between genetics and interdisciplinary curriculum development is essential when interdisciplinarity is defined as an important aspect for all or most university students, just like adding or swapping a gene to create desired properties in e.g. plants. In these cases, the role of the inserted DNA snippet; the genes or non-coding DNA, clearly illustrates the difference between the mandatory, elective, and free-elective courses. There is a restriction for how many genes a prefixed-sized chromosome may include as well as there is a clear restriction for the number of the courses in a curriculum. There is no such condition in offering free electives; a newly

**Table 4.** Mechanisms for increasing interdisciplinarity in a curriculum.

Curriculum change	Mechanism in genetics	Possibilities	Limitations	Reflection in building interdisciplinary degree
Student-driven alternative ways of executing a course/program	Mutations	Occur continually, possible to increase the prevalence, No need for planning	Random outcome: only some are useful – some useless, and some even harmful	Not a tool for systematic degree building. However, systematic RPL process enables diversity in degrees
Insertion of mandatory courses in curriculum	Gene inserts	Possible to develop a wanted property with a defined gene	Only a restricted number of genes fit in a chromosome	There is only limited space for including new courses (as mandatory or elective). Introducing a new course means a replacement of an existing course. It may call for a renewal of the entire degree program to take place
Insertion of free electives or a minor	Non-coding DNA insert	Riskless to fit new pieces of DNA in	Unknown exact impact	No need to change the original curriculum. Prerequisites for the minors and electives to be defined carefully to enable wide use of them
Combination of different disciplines into joint programs	Recombined chromosomes	Possibility to develop novel combinations of two parent chromosomes with different properties	<ul style="list-style-type: none"> <li>The exchanged parts must be equal in size</li> <li>The joint between the different strand DNAs must have matching ends</li> </ul>	<ul style="list-style-type: none"> <li>The prerequisites for the courses and programs must be defined carefully and flexible ways to fulfil these created.</li> <li>Choices between the courses in original curricula must be made</li> </ul>

introduced free-elective course does not require changes in the curriculum. Avoiding the negotiations on the removed courses makes an offering of the free electives as an attractive – in our example the most popular – choice for increasing interdisciplinarity. However, as the non-coding DNA has no exact acknowledged function, the free electives offer an uncertain tool for increasing interdisciplinarity as a freely chosen course may equally be from one's own as from another discipline. Our analogy suggests the genes, mandatory courses, might be more helpful in integrating the desired learning outcomes into the overall curriculum. This might help battle the issues of not linking interdisciplinary learning in students' own disciplinary learning (Richter and Paretti 2009; Rikakis, Tinapple, and Olson 2013).

Third, the genetic analogy of the formation of a recombined DNA by crossing over presents restrictions when increasing interdisciplinarity in a curriculum by a merger between two (or more) curricula. The length of the merged chromosome or a curriculum must remain the same. Furthermore, the positions of the genes in the chromosome or courses in the curriculum must be maintained. This means that the original curricula need to be matched with each other and the mandatory and elective courses between which the decisions need to be made, identified. Following approaches for dealing with the mandatory course were detected in our example: (1) courses from both disciplines remain mandatory, (2) courses become alternative choices, (3) courses are merged and the new merger course is kept mandatory, (4) courses are included in a common pool of elective courses. Notably, the last alternative was the most common in our example, but further studies are needed to determine the benefits of each approach.

The analogy between the DNA double strand and the duplicated nature of learning and learning recognition is related to all the tools for increasing interdisciplinarity in a way or another. As the bases of a DNA strand must match the right one in complementary strand (A-T, C-G), the learning requirement for a course and degree for the course execution and graduation must match. For the attempt of increasing interdisciplinarity in a curriculum this becomes pivotal in the case of defining prerequisites for courses or programs. Definition of the competencies that are needed for learning at the course or the program should be done learning-based instead of overall completed courses based. This is essential since what is considered foundational skills in each discipline might be different (Bovill and Woolmer (2019)). This requirement is visualised by the DNA joints in which the end of the new inserted strand must match with the countering strand of the original DNA (see Figure 3). The case of mutations or student-driven alternative ways of executing courses or programs we face similar question and focus in the duplicated natures in DNA and studies. In this case, the learning is acquired in non-standard ways; in student activities, in exchange, or during an internship. In genetic analogy, one strand of the DNA is not an exact match to the original. In a functioning process of recognition of prior learning, the preferable and non-prefer changes are distinguished. Here, our attention is drawn again into detailed matching between the essential learning and learning recognition.

### **6.3. Analogy as a tool**

Analogies are used in science in many ways as described in Section 2. Our analogy will serve as a tool for seeing the challenges from different point of view (Casakin and Goldschmidt 1999). It also provides a potential way to predict and explain the situation in a novel way as described by Gentner and Smith (2012). Moreover, our analogy helps in the knowledge building by pointing the differing elements (Gentner and Smith 2012) in mapping. We discuss here more in detail how our analogical tool may help in tackling the barriers and challenges when developing an interdisciplinary curriculum.

Many of the challenges in increasing interdisciplinarity are associated with the tradeoffs between the breadth and depth (Borrego and Newswander 2010). One of the challenges stemming from this dilemma is a tendency to try to fit too much content and learning goals in (Bovill and Woolmer 2019). Our chromosome model highlights this commonly known situation in a novel way by drawing an analogue of a limited length of the chromosome or a curriculum and restricted number of the genes or mandatory and elective courses at the curriculum. Furthermore, mapping the parallel



courses analogically to parallel genes in recombining chromosomes builds towards proper organisation of the studies, which was suggested as an essential approach by Van der Hulst and Jansen (2002). When organising studies in the parallel curricula and making choices of how to utilise the existing courses, the difference in our analogy, in fact, succeeds to point out the four alternative solutions for dealing with the parallel or competing courses. This differs from the situation with chromosomes, in which there is only either-or choices to be made with the genes.

The discussions between two disciplines are challenging as such, especially when the disciplinary distance is large. In our analogy, the focus is drawn to learning, learning recognition, and, especially in the prerequisites of the programs and courses in a novel way. The visualisation of the DNA joints, in which the strand of the inserted DNA must match with the counter strand of the original DNA (Figures 3 and 4). This request for detailed compatibility highlights the necessity for detailed definition of the prerequisites. These should be explicated as the required competencies instead of more generic completed courses. The detailed pre-requisite definition verifies on the one hand, that the adequate depth is achieved, and, on the other hand, that the unnecessary barriers are not introduced. The complementary nature of studies and of the DNA provide useful insight in the student-driven proposals for alternative ways for a course or program execution. Here, the assessment of non-standard learning and recognising prior learning map with mutation during DNA replication, which indicates the unpredictable nature of the outcome in terms of matching with learning requirements or the viability of the new DNA strand. In this point, our analogy highlights the importance of functioning RPL process over the use of the student-driven alternatives as a systematic tool for increasing interdisciplinarity.

The discussion related to the curriculum building becomes even more perplexing considering the power struggles described by Ruano-Borbalan (2019). We hope that our genetic analogue for curriculum development steers the discussion in an objective way and helps to keep the discussion in the central topics. In addition to maintaining the size of the curriculum without the common push to fit in too much (Bovill and Woolmer (2019)) and matching equally levelled courses and alternative ways of dealing with them the analogy steers toward detailed definition of the prerequisites for successful learning at any course. We hope these listed alternatives for dealing with the existing courses are useful in the tradeoff discussions of breadth and depth (Borrego and Newswander 2010; Sinnema and Stoll 2020).

Our model successfully predicts that the easy and the most popular solution (in our case study) for increasing interdisciplinarity, namely increased offering of the free-elective courses, does not necessarily lead to intended result. The mapping of the free electives with the non-coding DNA, with no specified function regarding to interdisciplinarity, strongly suggests that the easy solution does not necessarily serve as intended. In some cases, our analogue may help in visualising the handicap of the easy-looking solution in the educational leadership and administration. Similarly, our analogy gives a new tool for explaining the nature and pain points related to the development of interdisciplinarity in curricula for explaining the process to the administration.

Our analogy reaches its full potential in predicting (Gentner and Smith 2012) and envisioning the possibilities for varying levels of interdisciplinary interaction from one course to an entire merged curriculum (Figure 6). The cross-over chromosomes visualisation suggests that interdisciplinarity may vary between the mentioned degrees almost linearly. This will shift the discussion from either interdisciplinarity or no interdisciplinarity, to the degree of interdisciplinarity in a curriculum.

Further, thinking disciplines as parent chromosomes which cross-over to contribute to the interdisciplinary programs opens an interesting option of having more than one interdisciplinary curriculum or recombined chromosome. The multiple parallel possibilities of just two parent chromosomes crossing over are a source of ever-developing diversity, which enables different adaptations to the changes in the environment. Drawing an analogy between this capability and the variety of potential mergers between the disciplinary curricula, is a source of inspiration and encouragement for those involved in the process of interdisciplinarity increasing in studies.

## 7. Conclusion

We presented a novel analogy for interdisciplinary curriculum planning. Compared to the previously presented T-, Pi, and Y-shaped models of interdisciplinarity, we argue that our biomimetic analogy provides a notable upgrade. It does not restrict in visualisation of the combination of disciplinary competences but provides in-depth guidance for the degree engineering, it also combines the dual goals of interdisciplinary programs – learning specific interdisciplinary skills as well as becoming proficient in more than one discipline.

By mapping analogue structures and mechanisms from genetics, we have pinpointed the critical perspectives regarding the status of the courses, which encourage towards interdisciplinarity: the courses should be mandatory instead of free electives and the detailed definition of the prerequisites is crucial for enabling interdisciplinary study paths. We defined four possibilities for dealing with courses when forming a new interdisciplinary curriculum without increasing study burden nor reducing depth of the studies. In these, we have tools to maintain the existing value and competence and to evolve towards greater diversity.

Each of the mechanisms: mutations, inserts of genetic material, and recombining by crossing over highlight critical factors in terms of increasing interdisciplinarity in a curriculum. Behind each of these factors, there are decisions that impact interdisciplinarity. Our analogy aims at bringing neutral point of view in the discussions on restrictions and choices to be made when aiming at increased interdisciplinarity in a curriculum.

We showed how our analogy is valid and useful in different curriculum changes in two different universities. We also showed usefulness of the analogy in extending current thinking, for example by looking at a degree of interdisciplinarity as well as considering more than one 'child' or interdisciplinary program between two disciplines that can resemble the original curricula to a varying degree. Further, while not present in our case universities, we see a possibility to use this same model also for cross-university programs. Naturally, future work is needed to explore how exactly the proposed analogy supports curriculum development, when is it most useful, does it help addressing the common challenges in interdisciplinary curriculum planning and how it could possibly be further refined.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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From crossing chromosomes to crossing curricula - a biomimetic analogy for cross-disciplinary engineering curriculum planning

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