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March 7, 2024

INAUGURAL LECTURE

Pathways to innovative STEM education

EINDHOVEN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF APPLIED PHYSICS AND SCIENCE EDUCATION

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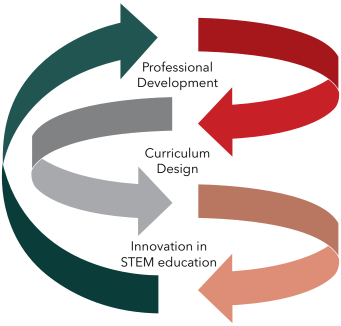
Introduction

Different paths have taken us to where we are now. We started our current positions around the same time, which presented us with the opportunity to deliver this inaugural address together. In the spirit of collaboration and innovation, we are connecting the dots between our interests in professional development, curricular design and innovation in STEM to identify pathways for developing the education of the future.



In this lecture we will focus on innovations in STEM education and the role that teachers can play in the design of new STEM education. We will also describe the professional development to support this process. In all three areas opportunities for educational research will be identified. Specifically, we will address the following questions:

1. Why is interdisciplinarity high on the agenda of secondary and higher education?
2. What does integrated STEM education look like in classroom practice?
3. What are the curriculum challenges related to innovative STEM education?
4. What are affordances and challenges for digital technologies that support STEM education?
5. How can professional development of teachers help innovate STEM education?
6. How does curriculum design in STEM education become an attractive teacher career pathway?

This is our shared vision for the future of STEM education, and we invite all of you to participate.

Jan, why is interdisciplinarity high on the agenda of secondary and higher education?

Interdisciplinarity

To understand and tackle complex societal problems[1], interdisciplinary research and student projects require contributions from multiple disciplines[2]. The impact of climate change is an example in which physics, chemistry, geography, biology and environmental expertise can help understand what is going on in our atmosphere. In this process, we make use of modeling techniques and algorithms from computer science, artificial intelligence and mathematics. Also, satellites with high-precision instruments are required to monitor the impact of climate change or to check if climate decisions are being implemented[3]. Moving on to solutions, apart from technological innovations, an understanding of human behavior and political decision-making is needed to make change happen. A consensus on how to move forward is very much needed.

What does this imply for higher and secondary education? Let's start with higher education. This interdisciplinary complexity is too much for each student to grasp in full detail. So, for each university program, it is important to make choices and then clarify what is meant when implementing interdisciplinary education[4, 5, 6]. Some study programs opt for learning objectives such as being able to collaborate across borders, understanding how your expertise can connect to that of others. Students in these programs build personal and professional skills to work in teams with other specialists, understanding what they can contribute and reflecting on other perspectives. Other study programs opt for an interdisciplinary focus from the start, with learning objectives across several disciplines that will help their students work towards more integral solutions. System thinking can help both groups of students understand this complexity[7]. In Figure 1, the most important

1 UN Sustainable Development Goals: https://sdgs.un.org/goals
2 Graham (2018a)
3 NASA (2024), Ozone layer repair actions after the 1987 Montreal Protocol includes satellite monitoring of chlorofluorocarbon (CFC) emissions. It sets an example for satellite programs designed to monitor greenhouse gas emissions worldwide.
4 Van den Beemt et al. (2023)
5 Twente Toolbox for Interdisciplinary Education: https://interdisciplinary-education.utwente.nl/
6 Klein (2017)
7 Habbal et al. (2024)

interdisciplinary student competencies are visualized based on interviews with academic staff[8]. Creativity and higher-order thinking skills are appreciated by all but the other items are valued differently according to how interdisciplinarity is perceived. Proper implementation of interdisciplinary education is a challenge as most of our teachers have been trained as specialists, feeling uncomfortable when having to broaden their teaching to topics beyond their own expertise. Multidisciplinary teacher teams can help overcome this problem. Hiring interdisciplinary experts from outside academia can also help implement interdisciplinary education. In the meantime, we can learn from our interdisciplinary student teams based at Innovation Space[9]. In these teams, each student can contribute their own expertise to the team challenge, while they also learn from their participation in the team endeavor[10].

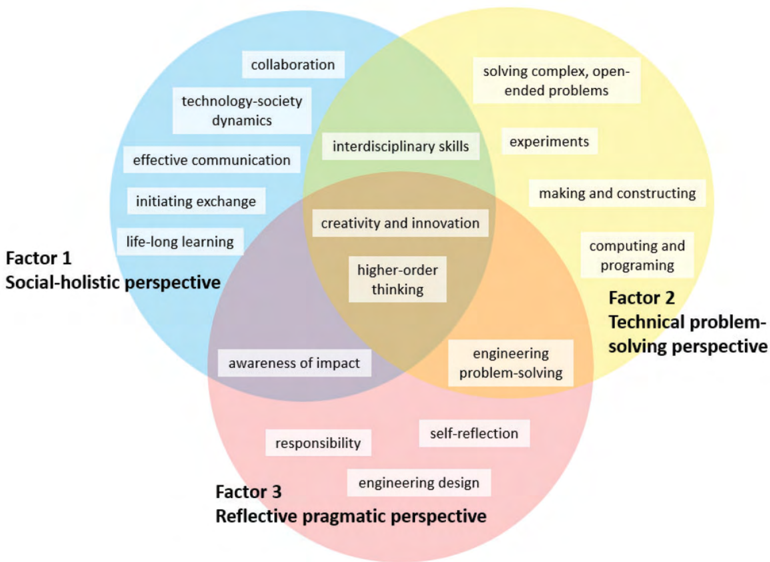


Figure 1. Perceptions of interdisciplinarity. Distinguishing and consensus items between and among groups of interviewed academic teachers (Ming et al, 2024).

8 Ming et al. (2024)
9 TU/e Innovation Space, https://www.tue.nl/en/education/tue-innovation-space
10 Bravo et al. (2024)

Interdisciplinarity is also strived for in secondary education. Phenomena and developments in society can be grasped if learners have some understanding of the connections. However, the school curriculum is very much aligned with the traditional school subjects and there is not an easy way to implement interdisciplinarity in the existing school subjects with there already being so many concepts to deal with[11]. Project weeks and capstone projects (in Dutch: 'profielwerkstukken') can have an interdisciplinary angle. Some schools implemented Science as a subject in lower secondary school. Life, Science and Technology (NLT) is implemented in approximately half of upper secondary schools. NLT is now also being developed for lower secondary schools[12]. In this way, young learners encounter a much wider range of science and engineering subjects. Another new school subject has been around for two decades now: Research & Design ('Onderzoek & Ontwerpen') is being implemented in Technasium[13] schools and some other schools as well. This school subject allows students to design and prototype solutions in teams, performing some research if needed. In this way, new interdisciplinary learning experiences are implemented in parallel to the traditional school subjects. These new subjects also effect study choice[14]. In a joint NRO project with regional school partners and Brainport,[15] new ways of implementing challenge-based learning are being developed in the context of sustainability[16]. A balanced approach of combining the introduction of new theory and concepts with in-depth understanding through application in projects is an interesting challenge in itself.[17]

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[11] Pieters (2022)
[12] https://www.verenigingnlt.nl/
[13] https://www.technasium.nl/
[14] Blume-Bos et al. (2020)
[15] Brainport Eindhoven
[16] Van der Veen et al. (2023a)
[17] De Jong et al. (2023)

Esther, what does integrated STEM education look like in classroom practice?

The innovative STEM classroom

Globally, as a society, we are facing and will continue to face significant challenges that require STEM graduates to not only be knowledgeable in the technical domain and capable of solving complex problems while working with others but also flexible, adaptable, resilient and able to operate in an increasingly digital landscape[18]. The profile of STEM graduates has been progressively changing over time from a very narrow disciplinary perspective with a relatively small set of professional skills to a broader disciplinary perspective, encompassing in-depth disciplinary knowledge in one or two subject areas and also knowledge of a broader range of subject areas together with a wide range of professional skills[19]. The advent of Industry 4.0, with intelligent systems (e.g., Internet of Things, Big Data, Artificial Intelligence), and more recently Industry 5.0[20], putting the human at the center of technological change, also demands constant skills renewal[21]. This constant need for skills renewal in turn necessitates changes at different levels of the educational ecosystem with the interplay of different stakeholders, including international and national policymakers in governments and professional bodies, educational institution leadership, program leaders, teachers and all educational professionals. How then are these needs and changes reflected in classroom practice?

A constant renewal in classroom practices requires us to consider two important aspects; one is what is taught (i.e., content) and the other is how learning and teaching are conducted in the classroom (i.e., pedagogy), be it online, face to face or in a blended fashion, noting that content and approach are intrinsically interlinked.

18 Fajaryati, Budiyono, Akhyar & Wiranto (2020)
19 Patrick & McShane (2023, October)
20 *Industry 5.0 – Towards a sustainable, human-centric and resilient European industry*, Publications Office of the European Union (2021) https://data.europa.eu/doi/10.2777/308407
21 Deming & Noray (2018)

STUDENT-CENTERED LEARNING APPROACHES

In the case of higher education, much of the disciplinary knowledge in STEM subjects and, in particular for engineering programs, is set by professional bodies operating at an international and national level and is reflected through accreditation frameworks that consider the knowledge needed for graduates to respond to industrial and societal needs[22,23].

Although traditional approaches such as lectures and tutorials are still often used in STEM higher education classrooms, we need to turn to different approaches of learning and teaching in order to develop an integrated knowledge base together with a wide range of professional skills. These include pedagogies that put the student at the center of learning[24], foster social and experiential learning[25] and situate learning in a real-world context moving from the abstract to the tangible[26] and fostering transfer from theory to practice[27]. Pedagogical approaches based on a process of inquiry, such as problem-based learning[28] that started in the 60s in the medical field[29], allow the development of both disciplinary knowledge and professional skills[30]. Innovation around inquiry-based pedagogies has brought us other variations such as project[31], scenario[32] and challenge-based learning[33], among others. These are implemented across STEM programs in higher education in single and cross-discipline courses and programs with or without the involvement of external stakeholders (e.g., using scenario and project-based learning, with examples at UCL and Linköping University respectively) or in interdisciplinary settings (e.g., project- and challenge-based learning, with examples at Aalborg University, Tecnológico de Monterrey, the University of Twente and TU/e) (see Figure 2).

[22] Ho, Kortian, Huda & Lee (2023)
[23] Bolton, Glassey & Ventura-Medina (2023)
[24] Land, Hannafin & Oliver (2012)
[25] Kolb (2014)
[26] Lave & Wenger (1991)
[27] Gray & Holyoak (2021)
[28] Hmelo-Silver (2004)
[29] Graaff & Kolmos (2007)
[30] Mabley, Ventura-Medina & Anderson (2020)
[31] Noordin, Nasir, Ali & Nordin (2011)
[32] Errington (2008)
[33] Gallagher & Savage, T. (2023); Doulougeri, van den Beemt, Vermunt, Bots & Bombaerts (2022)

Figure 2. Sustainability student teams of Eindhoven University of Technology: CASA, CORE, Enactus, Falcon, FruitPunch, InMotion, Solar Team, SOLID, TU/ecomotive, University Racing Eindhoven, VIRTUe and Team Energy. Photo by Bart van Overbeeke Photography.

VIRTUAL LEARNING

Similarly, for years now, there has been an increase in the use of virtual learning environments (VLEs) to support blended learning. Platforms such as Canvas, Blackboard, Moodle and MS Teams offer access to digital materials (e.g., files, videos), activities (e.g., quizzes, lessons) and spaces for learners and teachers to interact (e.g., discussion fora, wikis, video meetings) outside the physical classroom[34]. VLEs afford learners adaptability and flexibility for both individual and social learning and, in institutional settings, are designed to mirror or to connect to some extent with the physical classroom. Connectivity between VLEs and the physical classroom further promotes student-centered approaches (e.g., flipped classrooms[35]).

[34] Anthony, Kamaludin, Romli, Raffei et al. (2022)

[35] Karabulut-Ilgu, Jaramillo Cherrez & Jahren (2018)

In STEM disciplines, both in secondary and higher education, we also see much more use of augmented reality and virtual reality[36] to support practical and experiential learning (Figure 3), simulations (e.g., roleplaying, simulated discussions) that require interactions with people at different cognitive levels[37] and online scenarios to facilitate the development of skills and knowledge using complex problems crossing different domains[38].

Figure 3. Augmented reality teaching with a heart model for Medical Science and Technology (MST) students of the Department of BioMedical Engineering at TU/e Innovation Space. Thanks to the use of augmented reality apps, the students can still see the surroundings and each other, as well as read the paper instructions next to the XR glasses. The Heart & Blood course is being discussed with the help of a 3D hologram of a heart. This is a heart that beats, which can be viewed from all angles and touched if wearing a HoloLens on one's head. Photo by Bart van Overbeeke Photography.

We also see fully online virtual classrooms such as those found in massive open online learning (MOOC) courses, collaborative learning based on problem-based learning (e.g., open networked learning[39]) and distance learning programs based on the Community of Inquiry (CoI) model[40] (e.g., Athabasca University).

36 Di Lanzo, Valentine, Sohel, Yapp, Muparadzi et al. (2020)
37 Chernikova, Heitzmann, Stadler, Holzberger, Seidel et al. (2020)
38 Mio, Ventura-Medina & João (2019)
39 https://www.opennetworkedlearning.se/; Creelman, Kvarnström, Pareigis, Uhlin & Åbjörnsson (2021)
40 Swan, Garrison & Richardson (2009)

Social media platforms and digital applications, which are outside of the institutional boundaries of VLEs, have also been adopted and therefore legitimized as part of the learning environment in virtual classrooms. This shows how permeable the boundaries are between the formal and informal – physical and virtual – learning spaces[41].

Despite the advantages that virtual learning environments, digital tools and digital platforms offer, there is still much that we need to understand about moving learning outside the traditional classroom[42], questions about how the connected spaces (virtual and physical) offer flexibility, adaptability and inclusivity as part of a network and the need to address how the relationship between spaces and interaction between different actors (e.g., teachers, students) hinder or support social learning.

What we see in teaching and learning practices nowadays in both secondary and higher education settings is a diverse range of approaches (new and old) with many using real-life situations (i.e., knowledge integration) and teamwork (i.e., social learning). These approaches aim not only to develop a range of knowledge and skills but also to support diversity and inclusion.

Ultimately, to meet the diverse demands of a future graduate profile, we need to employ a range of learning approaches in the classroom and, in doing so, we need to be mindful of balancing:

- the roles of the student and the teacher,
- individual and team activities,
- the open-endedness of problems and challenges,
- the disciplinary specificity and complexity with a systems approach,
- inter- and trans-disciplinarity and single discipline.

We also need to consider how all these are scaffolded within a course and in curricula as a whole. Any innovation should be aligned with the overall curriculum philosophy.

Here, I have presented examples of innovative educational practices without going into detail on the design of educational activities which need to be aligned with both learning objectives and assessment practices[43]. How these classroom approaches are reflected in a program requires careful consideration of curricular design.

41 Tess (2013)
42 Thomas (2010)
43 Biggs & Tang (2014)

This leads us to another question. Nienke, what are the curriculum challenges related to innovative STEM education?

Curriculum challenges related to innovative STEM education

This is an important question, as innovating STEM education is an exciting journey but indeed also needs careful consideration regarding the curriculum. A curriculum is a design for learning[44]. And from that perspective, challenges exist regarding consistency-making and coherence-making. I will briefly introduce both here.

CONSISTENCY-MAKING: TOWARDS CURRICULUM CLARITY

For school teams, it is important to create clarity about the ways in which STEM education is part of their school-based curriculum[45]. Among other things:

- it needs connection with the horizontal relationships between the mono-disciplines and the rich interdisciplinary challenges[46] (e.g., Figure 4). For instance, will students start with mono-disciplinary subjects and then start integrating these, will they do it the other way around or will it be a combination of the two?
- it requires a consideration of the sequencing of theme-related knowledge and skills over a longer period. For STEM education, a spiral[47] curriculum allows learners to deepen and widen their understanding over time. In each iteration, students build upon previous knowledge and skills (e.g., Figure 5).

44 Nieveen, Van den Akker & Voogt (2023)
45 Skilbeck (1998); Nieveen, Handelzalts & Van Eekelen (2011)
46 Bransford, Brown & Cocking (2000); Menken & Keestra (2016); National Research Council (2012); Nypels & Kamp (2022)
47 Bruner (1960)

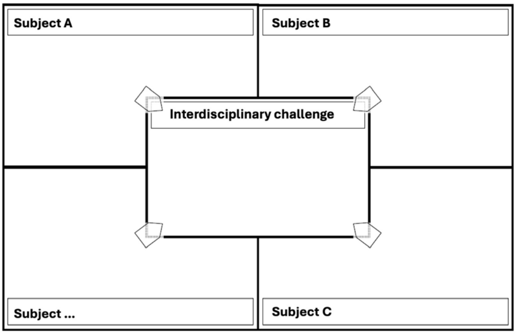

Figure 4. Horizontal relationships

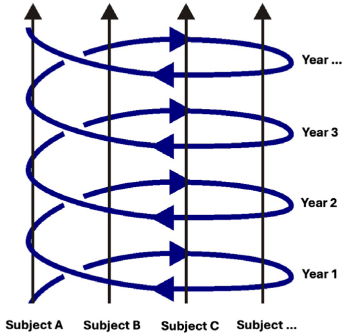

Figure 5. Sequencing

- and it needs decision-making on all curriculum components and their linkages while taking into consideration the underlying 'why' question[48], as illustrated by the curricular spider's web[49] in Figure 6. The spider's web, as a metaphor, points to both the flexibility and the vulnerability of a curriculum.

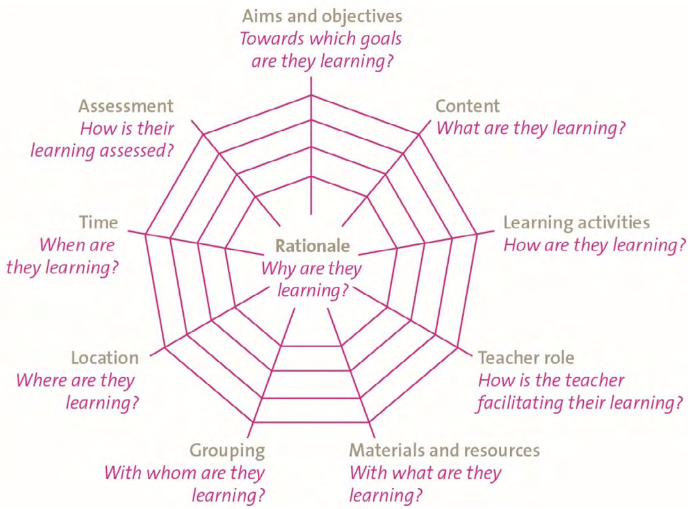

Figure 6. Curricular spiders' web

[48] See also the first two questions in this inaugural lecture, referred to by Jan van der Veen and Esther Ventura-Medina

[49] Van den Akker (2003)

These (and other) consistency-making decisions work towards a clear image of STEM education and prevent curriculum fragmentation in a school. However, in practice, this is easier said than done. Support is needed. This brings me to the second set of issues, related to curriculum coherence.

COHERENCE-MAKING: TOWARDS A SHARED SENSE OF DIRECTION

It would be of major help for school teams if the educational system would show at least some coherence with respect to what we collectively envision regarding STEM education[50]. Coherence is expressed by three types of flow[51] throughout the various nested educational settings[52] (the classrooms, the schools and the regional, national, and international settings): (1) semiotic flow (e.g., shared supportive language and concepts); (2) material flow (e.g., related supportive materials and tools); and (3) social flow (e.g., joint work). In the Netherlands, curriculum coherence for secondary STEM education needs to be improved[53].

For instance, regarding our policy language (as part of semiotic flow), it is not clear whether we - as a country - collectively agree that schools and teachers should embed interdisciplinary education in the school programs. The emphasis on standardized central exams in upper secondary education for the disciplinary subjects (e.g., mathematics, physics and chemistry) results in a dynamic in which teachers and school leadership feel pressured to focus on exam preparation rather than engaging students in meaningful integrated STEM education. For lower secondary education, the Dutch national curriculum framework remains quite open with respect to the core objectives. This leaves many complex curriculum decisions to the school teams.
What we need is a common rationale, a narrative that transcends settings and answers the fundamental question of: 'what knowledge and skills are of most worth?'[54]. Such a rationale, preferably translated into actionable design principles, would create a (more) structured space for curriculum design in all settings,

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50 Nieveen & Van den Akker (2023)
51 Deleuze & Guattari (2003); Dempsey, Doyle & Looney (2021)
52 Thijs & Van den Akker (2009)
53 Sijbers & Woldhuis (2021); Taminiau, Ottevanger, Pieters, Woldhuis, Sijbers, Spek, Schalk, Rodenboog & Van Graft (2017)
54 The essential curriculum question introduced by Herbert Spencer (1860)

offering a clear sense of direction while striking a balance between the purposes of education[55].

Likewise, STEM teachers need resources and lesson materials (examples of material flow) that guide, inspire and encourage teacher teams in their school-based curriculum design efforts, materials they can tailor to their students' needs and the context of the school[56]. Instead of turning to mainstream publishers, schools that embrace innovative STEM education look for alternative support in the educational infrastructure, such as the Technasium Foundation[57], the NLT Association[58] or work within their own collaboratives on module design[59].

Finally, coherence-making requires social flow across the curriculum settings in varying compositions[60]. This means open dialogue and platforms for joint work among teachers, school leaders, policymakers and pedagogical content knowledge (pck) experts, as well as parents and the public at large. Shared sense-making throughout the system is paramount to assisting school teams in their important work. Collectively, we are at the beginning of understanding curriculum design as a social practice, but much is yet to be learned.

The challenge remains: how do we provide schools and teachers with the professional space to tailor and innovate their curricula while maintaining a common sense of direction and safeguarding educational quality? Finding a proper balance is delicate[61]. Our commitment to addressing these and other curriculum design challenges requires ongoing curriculum research activities, focusing on the practices of school-based curriculum development and strengthening connectivity within and across settings. In doing so, let us not forget that a curriculum is a design for learning with student learning at the center in *all* settings. From that point, we also need to look into the future.

55 A framework with three domains of purpose, i.e., qualification, socialization, and subjectification (cf. Biesta, 2020) is often used for starting discussions regarding the rationale. Balance varies over different stages of schooling and depends on dominant values in specific contexts.
56 Pepin (2018)
57 Around 100 Technasium schools are connected to the Technasium Foundation (https://www.technasium.nl/)
58 Around 220 schools provide the elective Nature, Life and Technology (in Dutch: Natuur, Leven en Technologie); https://www.verenigingnlt.nl/
59 See, for instance, a joint project with schools and ESoE on embedding Challenge-Based Learning https://www.nro.nl/onderzoeksprojecten/challenge-based-learning-uitdagend-onderwijs-voor-een-duurzame-toekomst.
60 Pieters (2022); Soini, Pyhältö, Haverinen, Sullanmaa, Leskinen, & Pietarinen (2022)
61 Nieveen & Kuiper (2021); Scientific curriculum committee (2020)

Looking from a future perspective, Esther, what affordances and challenges do you see for digital technologies that support STEM education?

Affordances and challenges of digital technologies to support STEM education

We looked before at some of the classroom practices that offer opportunities for interdisciplinary learning, including the integration of digital environments and tools which are ubiquitous in today's classrooms. During the COVID pandemic, we saw a rapid increase in the use of digital technologies and tools. In the future, their presence is only expected to increase, making for a digitally-rich learning classroom. Thus, the question here is: how could digital environments and tools shape innovation in STEM education?

Before we delve into this, I would like to make a distinction between 'digitalization' and 'digitization'. I will refer to 'digitalization' as the automation of processes to simplify operations (e.g., automatic marking/grading of quizzes), which is the focus here. This is in contrast to 'digitization', which refers to the "fully digital creation of information and data without [necessarily] a physical or analogue counterpart" (e.g., an electronic file, a music CD) – as opposed to an analogue format (e.g., a paper file, a vinyl record) – but which does not involve automation processes[62]. Therefore, I will concentrate here on learning processes and not so much on artifacts (e.g., textbooks, videos).

[62] Clarke (2019), see also Vrana & Singh (2021)

OPPORTUNITIES OFFERED BY DIGITALIZATION AND DIGITAL TECHNOLOGIES TO CLASSROOM PRACTICE

There is already plenty of technology that allows us to digitalize much of learning. In VLEs (e.g., Moodle, Canvas, Blackboard), the use of automatic marking and feedback loops[63] is a good example. More recently, with the development of artificial intelligence based on large language models (e.g., ChatGPT, Google Bard) and specialist chatbots[64], it is not difficult to foresee virtual 'assistants' or 'companions' that could interact with and support both students and teachers in managing learning processes. These 'assistants' would not be a replacement for the teacher but could be another social actor (i.e., embodied conversational agent)[65], as we already see in computer games such as Second Life and The Sims. These 'virtual companions' could support individual learners simultaneously, both synchronously and asynchronously, making it possible to attend more carefully to students needs and the creation of tailored learning experiences and journeys.

We also see an increase in the use of applications that aim to support social processes by providing individual avatars, proximity chats and private spaces (e.g., Wonder, GatherTown, Sococo)[66] in formal or informal 'virtual classrooms'. For years, we have used spaces and tools for collaboration to support team learning (e.g., discussion fora, wikis, social media)[67]. More recently, we have seen an expansion in eLearning platforms used in professional development courses that offer customized set-ups for online learning, including possibilities for gamification, instructor-led sessions, social learning and more, in a single environment (e.g., Docebo, Learning Pool)[68]. These platforms include machine learning and generative artificial intelligence that support a range of different languages for both text and speech. In this respect, these types of learning environments could offer inclusive and equitable learning experiences and support a wide range of learners' needs.

63 Hahn, Navarro, De La Fuente Valentín & Burgos (2021)
64 Slepankova (2021); Kasneci, Seßler, Küchemann, Bannert, Dementieva et al. (2023); De Putter (2023).
65 Muhle (2016)
66 Latulipe & De Jaeger (2022, February); see also https://www.gather.town/; https://www.sococo.com/
67 Popescu (2014)
68 See https://uplearning.nl/; https://learningpool.com/

Figure 7. The team of the future? Left: image generated with Canva (Magic Studio™). Prompt used: "a group of students and a humanoid working together around a table" (filmic style). Right: image generated by Canva (Magic Studio™). Prompt: "a group of students and a humanoid robot working together around a table."

Likewise, for years we have heard of robots being used both as pedagogical tools (e.g., for languages, art, physics and mathematics education)[69] to achieve short-term learning goals and also as social actors in collaborative child tutor learning, supporting broader general development[70].

Although there are many challenges in the area of robotics due to the complexity of integrating mechanics, computer science, electronics, human interaction and educational knowledge[71], it will not be too long before we also find humanoid robots alongside students and teachers in both secondary and higher education classrooms. The future team might look similar to the generated images depicted in Figure 7.

Despite the fact that there is a great deal of technological development, the use of technology in the current classroom is still in its infancy. There are many advantages to introducing and using digitalization in learning but we must ask: how do we know whether these digital environments and tools enhance or hinder learning?

[69] Tuna, Tuna, Ahmetoglu & Kusco (2019)
[70] Ekström and Pareto, (2022)
[71] Stasse & Flayols, 2019

CHALLENGES OF LEARNING IN A DIGITALLY-RICH ENVIRONMENT

The intersection of two domains, the development of technology for education and the understanding of interdisciplinary and social learning in digitally-rich settings, leave us with many open questions. On one hand, in the domain of social learning within the physical classroom, we are still actively researching:

a. how students learn and work in diverse teams (e.g., cultural background, disciplinary domain, across stakeholder groups) to arrive at sustainable socio-technical solutions[72].
b. how 'disciplinary', 'interdisciplinary' and 'transdisciplinary' knowledge is developed while learning in teams[73].
c. how working in teams impacts the development of a student's identity (i.e., personal, social and professional)[74].
d. how identity development in turn impacts graduate career paths and future professional choices[75].
e. how students in these learning settings develop durable lifelong learning skills (e.g., self-regulation, autonomy, resilience, empathy)[76].

On the other hand, the rapid adoption of digital tools and the development of sophisticated virtual environments leave us with further questions around where and how learning takes place. Despite the advantages that virtual learning environments offer, the complexity that they bring to education still leaves us with much that we need to understand about moving learning outside of the traditional classroom[77]. Questions about how the connected spaces (virtual and physical) offer flexibility, adaptability and inclusivity as part of a network and how the relationship between spaces and interactions between different actors (e.g., teachers, students, artificial intelligence agents) hinder or support social learning are still open.

[72] McQuade, Ventura-Medina, Wiggins & Anderson (2019); Yu, Shen, Cheng & Bao (2022); McQuade, Ventura-Medina, Wiggins, Hendry & Anderson (2020); Creelman, Kvarnström, Pareigis, Uhlin & Åbjörnsson (2021)

[73] Bombaerts, Martin & Doulougeri (2022, October); Van den Beemt, MacLeod, Van der Veen, Van de Ven, Van Baalen et al. (2020)

[74] McQuade (2020)

[75] Tomlinson & Jackson (2021)

[76] Doulougeri, Vermunt, Bombaerts, Bots & de Lange (2021); O'Connell, Stöhr, Wallin & Negretti (2023); Mabley, Ventura-Medina & Anderson (2020)

[77] Thomas (2010)

We can draw parallels between the virtual and the physical classroom using the concept of digital twins (DTs)[78]. DT platforms that interconnect physical and virtual spaces and processes are becoming more mainstream in industrial applications[79]. Although not widely used yet in the context of education, a digital twin of the classroom could allow us to envision spaces with movable and permeable boundaries using additional resources, such as virtual reality and augmented reality sets, mobile applications, computer simulations and avatars of students, teachers and robots connected to their 'mirror images' (see Figure 8). Digital twins are envisioned to become intelligent platforms where not only processes but abstract ideas can exist[80] and where data-informed learning can take place.

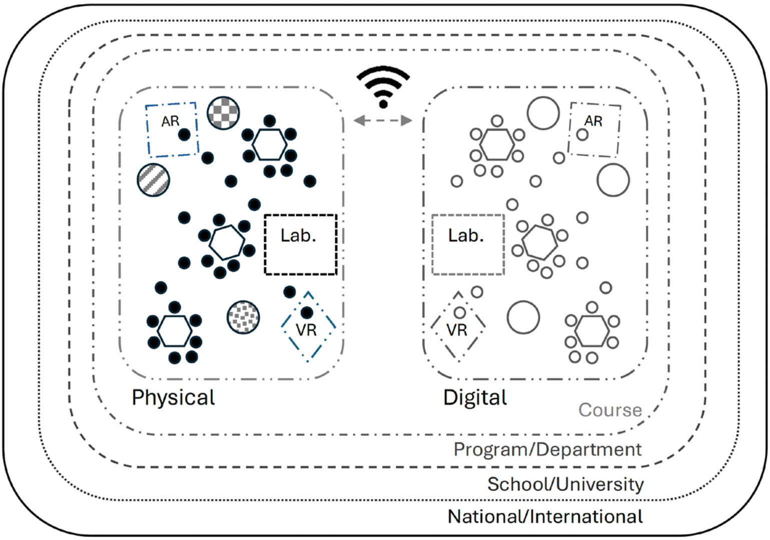

Figure 8. Depiction of a digital twin classroom (i.e., connected classroom) with example resources, e.g., virtual reality (VR), augmented reality (AR), laboratories (Labs), teacher, students (circles), within the educational ecosystem.

[78] A digital twin is "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems", see Van der Horn & Mahadevan (2021)

[79] Jiang, Yin, Li, Luo & Kaynak (2021)

[80] Grieves (2023)

Despite the fact that these virtual environments are data-rich and can inform learning, we still do not know enough about how learning in these smart adaptive digital environments takes place[81]. Collecting and analyzing large datasets of learners' online behaviors (e.g., how students work in the physical and virtual learning environment, how they engage with different artifacts and activities, how students interact with peers and teachers) can provide valuable information about how learning takes place. In turn, this provides a basis for developing understanding and learning models. However, for learning models to be useful for further smart systems development using, for instance, artificial intelligence and machine learning algorithms, they need to be robust and reliable[82]. Any model that attempts to 'simulate' learning processes must not only include cognitive processes but also capture the nuances of social learning and interactions that are bound by cultural and social norms intrinsic to the different levels of the educational ecosystem: classroom, department, institution, nation.

I mentioned before that digitalization and digital tools, at least when deployed sensitively, could potentially lead to inclusive and equitable learning, along with better informed and tailored learning experiences. However, we must be cognizant of the risks of using them insensitively. Some of the biggest challenges that we face in relation to the adoption of these technologies are access, fairness, use of data, privacy, human autonomy, transparency and clarity around the technology[83].

For us to learn more about learning in a digitally rich environment, it is necessary firstly to examine our current theories and models of learning and digital learning. Secondly, we must design and implement innovations in digitally rich learning spaces grounded in state-of-the art knowledge, aligning learning objectives and acknowledging contextual differences. Finally, we need to evaluate the outcomes of such innovations to generate new insights[84]. Moreover, it is necessary to consider the step beyond 'digitalization' and look at the 'digital transformation' of the educational ecosystem, involving a collaborative effort between policymakers, educational institutions at all levels (i.e., primary, secondary, higher education), wider society and obviously students. These efforts require commitment to professional development in order to ensure successful implementation and learning in these complex environments.

[81] Cheung, Kwok, Phusavat et al. (2021); Vonk-Franke, Ventura-Medina, Snijders, Matzat, Zhang et al. (2023)
[82] Hanif, Khalid, Putra, Rehman & Shafique (2018, July)
[83] AI HLEG (2019). Ethics Guidelines for Trustworthy Artificial Intelligence. High-Level Expert Group on Artificial Intelligence
[84] McKenney & Reeves (2014); Laudonia, Mamlok-Naaman, Abels & Eilks (2018)

Jan, how can professional development of teachers help innovate STEM education?

Professional development

Professional development of teachers can have benefits for the quality of education, while it can also be an ingredient in making the teacher's job more attractive, possibly even as a career steppingstone in schools or universities. While our main task is educating students, there are also tasks related to developing new education, coaching of colleagues, and managing and organizing education. Each direction includes personal and professional development. School development and strong teacher teams are also valuable outcomes.

I will now zoom in on professional development related to interdisciplinarity in schools. For good interdisciplinary education, we need to prepare our teachers well, starting in the teacher education program. Teamwork is essential as teachers cannot cover all subject areas that relate to interdisciplinary challenges. Teachers can deepen their coaching skills or they can develop certain design competencies. Content-wise, some new concepts or methods can be trained, for example green competencies[85, 86]. These professional development steps will strengthen the ability of teachers to cover content and skills outside their current expertise. Senior teachers can play a role in coaching young colleagues as part of the learning culture in schools, which can also include intervision. Teachers can opt to work in teams across different schools in their region. Such professional learning communities can connect experts from different schools. Their goal might be to optimize their lesson design or some learning activities, such as dialogues and argumentation[87]. This will help deepen the learning experience while also impacting equal opportunities if we learn to understand better how our interactions can either hinder or stimulate learners[88, 89]. Visiting each other's lessons in formats such as lesson study[90] can be an excellent means of professional development. Mixed teams of students, teachers and researchers can develop

85 Stouthart (2023)
86 The EU GreenComp Framework; Bianchi et al. (2022)
87 Diepenbroek (2022)
88 Hendrickx et al. (2023)
89 Vos (2024)
90 De Vries, Goei & Verhoef (2022)

new science and engineering materials, projects, practicals and simulations. ESoE colleagues are ready to help organize these professional learning communities. Our current list of topics includes quantum physics[91, 92], building houses[93], educational research[94], formative evaluation[95] and sustainability. Training options for teachers should be available if new topics are introduced in the national curriculum. Regional and national teacher conferences and Beta4all[96] courses show that STEM teachers are eager to upgrade their expertise if linked to topics and skills they need in their profession.

Teaching is a core activity in higher education, and we like to do it well. So far, much of the professional development of university teachers has been informal. By working together, our way of teaching is handed over to the next generation. The 250 hours of basic training, called the university teaching qualification (UTQ), is relatively small compared to the minimum of 1,600 hours that is required for a teaching license in schools. The UTQ helps teachers to develop basic teaching skills. Also, a shared language is developed, which is helpful if education issues are discussed[97]. New plans for continued professional development beyond the UTQ are being implemented in all Dutch universities[98]. Mutual recognition of these qualifications is crucial to raising the standards and for staff mobility. TU Eindhoven is also planning the next steps. A needs assessment amongst teachers showed that TU Eindhoven teachers would like this professional development to connect well with their personal educational tasks[99]. The group of consulted teachers are eager to network with other staff that work in similar settings, such as developing challenge-based learning projects[100] or integrating e-learning options in their courses. Right now, the redesign of the TU/e bachelor's programs is a rich context for such professional development, both informal and formal[101]. The NRO Teachers2Learn project[102] is zooming in on the professional development options in the context of educational innovations, working together with 20 other Dutch institutes of higher education. Research into ways to arrange some of the practicals

91 Thielen (2023)
92 Vilarta Rodriguez et al. (2020)
93 Van Harten (2024)
94 Schellings et al. (2023)
95 Maessen et al (2024)
96 https://beta4all.nl/, see also Meulenbroeks et al. (2018)
97 Kottmann (2023)
98 Mulder & Adams (2023)
99 Gomez Puente et al. (2024)
100 Van den Beemt (2023)
101 Van Dijk et al. (2020)
102 https://teachers2learn.nl/, see also Stevens et al. (2023)

into a more open format is another example of higher education projects in which we collaborate with other universities[103]. A third example is the STUKO[104] coalition of higher education institutes, zooming in on improved training of students who perform teaching tasks. Well-trained students can be a great asset both for the students they supervise and with respect to the development of their own professional skills[105, 106].

In the international context, the educational career framework[107] with four levels is widely used, linking the teaching expertise levels to HR frameworks. This framework can also be used to identify what professional development is relevant for each level (Figure 9).

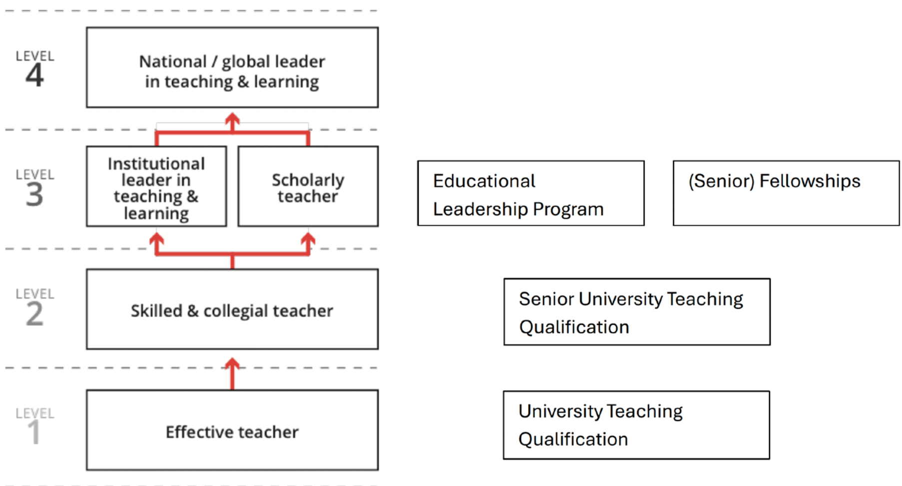

Figure 9. Educational Career Framework (Graham, 2018b) and professional development options.

[103] Bradbury et al. (2022)
[104] https://stuko-project.nl/
[105] Dekker, Thurlings et al. (2024)
[106] Van der Veen et al. (2023b)
[107] Graham (2018b)

The framework was also used to link to the different Comenius grant options[108]. Challenges remain as academic careers are often primarily linked to research output and successful research grant applications. Discussing educational efforts and plans in annual interviews is often overlooked[109]. A more balanced system is now worked out through Recognition & Rewards projects[110] at all Dutch universities. Team science and recognition of excellent teaching are high on the agenda of these projects. Developing solid evaluation methods for education is part of this process. The longitudinal Teaching Cultures Survey[111] is monitoring progress and it would be wonderful to see some progress in the next measurement. At TU Eindhoven, we have the innovators, trainers, researchers and support staff to inspire academic teachers that design or redesign their education.

Combining the development of education with professional development and research into what works is a growing part of our work, with special attention for subject didactics in both secondary and higher education. Strong regional, national and international networks[112], such as school partnerships, 4TU.CEE, EWUU, EuroTeQ, SEFI and CDIO, can accelerate innovations and professional development if we share expertise and resources.

[108] NRO Comenius program Leadership Fellows 2023
[109] Graham (2022)
[110] https://recognitionrewards.nl/
[111] https://teachingcultures.com/Findings/
[112] For example: TRION, OMO, 4TU, EWUU, EuroTeQ, SURF, Comenius network, SEFI and CDIO

Nienke, how does curriculum design in STEM education become an attractive teacher career pathway?

Teachers as designers of STEM education

Before going into more detail regarding this intriguing question, I will first elaborate on the general idea of teacher career pathways. This idea is linked to a great societal concern, that of the imminent shortage of teachers. As we look ahead to 2027, projections paint a picture with an anticipated deficit of over 2000 full-time teaching positions in secondary education, especially in subjects such as mathematics, physics, chemistry, computer science and classical languages[113].

To address this challenge, research[114] highlights key factors to increase the attractiveness of the teaching job, like compensation, induction support for new teachers and the improvement of working conditions, including shared decision-making and resources for career development. To this latter end, a significant step was taken in the Netherlands by developing a framework for teacher career pathways. This framework[115], illustrated in Figure 10, serves as an informal map for teachers to navigate their careers, aiding school leaders in supporting professional growth and identifying potential within their institutions.

Related to the curriculum challenges that come into play when innovating STEM education in schools[116], the 'western slice' of this framework, pointing to career pathways in 'developing teaching and learning' (or, in other words, 'curriculum design'), is of particular interest. For teachers, the framework emphasizes moving up and along by becoming an expert teacher, moving sideways by adding new roles to the role of classroom teacher (in this case, that of a designer) and adding layers of system (by taking design roles in team, school, regional or national settings).

[113] Onderwijsraad (2023)

[114] Including studies by the European Commission (2020); Podolsky et al. (2016), Vroonhoven (2020), Asscher, Damen, Kasem, Darrazi, Rotteveel & Büller (2022)

[115] Snoek, de Wit & Dengerink (2020)

[116] See notions regarding question 3 in this inaugural lecture 'curriculum challenges related to STEM education'.

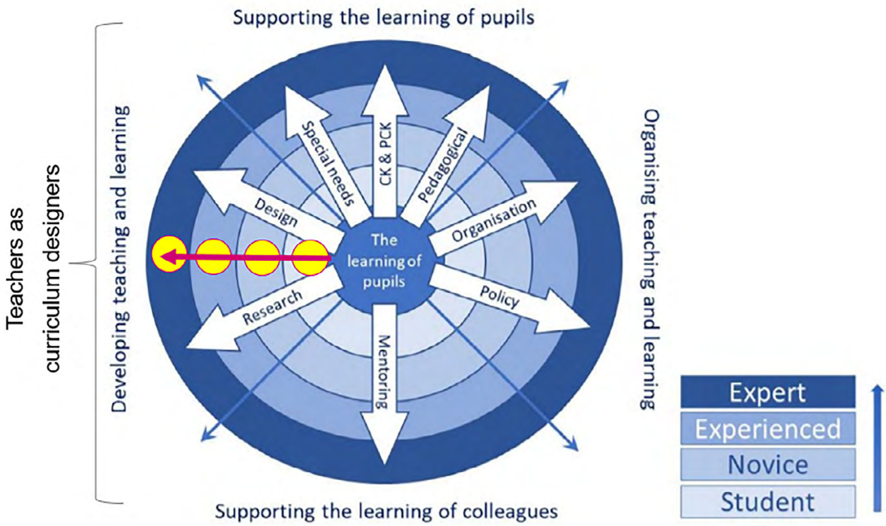

Figure 10. Framework of teacher career pathways

School-based curriculum development usually involves a range of design tasks[117]. Teachers who are working on smaller design tasks (for instance, lesson planning) usually need a smaller amount of curriculum design capacities compared to teachers who work on subject integration and design accompanying innovative lesson materials in long-term collaborations with their peers. Ideally, the curriculum design capacities of teachers match with the task complexity and the availability of a supportive school culture and infrastructure[118]. Unfortunately, this is not always the case, leading to teams struggling with the complexity of the design tasks. When studying these issues more closely[119], teams report problems related to one or more curriculum design perspectives. Here, I refer to them as 'what', 'how' and 'with whom' questions (first column in Table 1)[120]. In earlier studies, six underlying

[117] Marsh & Willis (2007); Law & Nieveen (2010)

[118] Handelzalts, Nieveen & van den Akker (2019; Priestley, Biesta & Robinson (2015); ESoE colleagues are performing a study on promoting a sustainable research culture to increase educational quality in schools https://www.nro.nl/onderzoeksprojecten/een-duurzame-onderzoekscultuur-bevorderen-onderzoeksmatig-werken-aan-onderwijskwaliteit

[119] Nieveen, Handelzalts, & van Eekelen (2011); Handelzalts, Nieveen & van den Akker (2019); Leeman, Nieveen, de Beer & van der Steen (2020)

[120] Goodlad (1979)

types of design expertise were distinguished[121]. For this lecture, I have related each expertise to these three curriculum perspectives (second column in Table 1) and have illustrated these with STEM education-related examples (third column in Table 1).

Table 1. Curriculum design capacities

Curriculum perspectives	Related curriculum design expertise	Examples from STEM education
Substantive perspective (**'what'** questions, such as: What curricular choices can we make? What is our rationale? What are features of the constituent parts of the curriculum?)	**1. Subject matter expertise**	E.g., related to the climate crisis: CO_2, combustion, photosynthesis, carbon sinks, tipping points, lifecycle analysis, zooming in and out, modeling.
	2. Pedagogical content knowledge	E.g., assisting in perspective taking (especially when students are used to demarcated mono-disciplines), conceptual change methods, product and process-oriented feedback.
Technical-professional perspective (**'how'** questions, such as: How will we go about the design task? What design strategy will we follow? How and when do we plan and perform evaluation activities?)	**3. Curricular problem-solving expertise**	E.g., analysis (of learners, context, concepts, interactions), design (e.g., brainstorming, prototyping), construction (authoring materials), evaluation (screening, expert appraisal, micro-evaluation, try-out), acting responsibly throughout the process.
	4. Consistency-making expertise	E.g., creating clarity about the curriculum components, horizontal linkages within and between subject areas, sequencing with the help of learning strands, zooming in and out to the overall rationale and context of the school, national curriculum frameworks.
Social-political perspective (**'with whom'** questions, such as: Who should be involved in the decision-making process? Who decides on this? What is the role of the teachers and school leadership?)	**5. Coherence-making expertise**	E.g., using shared concepts, language and tools, interdisciplinary collaboration of teachers, pedagogical content knowledge (pck) experts, negotiation with school leadership, change-making skills.
	6. Reflective expertise	E.g., reflection for, during and on actions to build and ensure confidence, resilience, empathy and open-mindedness to improve the quality of teaching and design practices.

[121] cf. Huizinga, Handelzalts, Nieveen & Voogt (2014)

The three perspectives (what, how, with whom) reveal that curriculum design efforts need to be seen as a multi-layered social practice[122] as well as a substantive and technical professional practice.

Figure 11 depicts a diversification of curriculum design tasks throughout a teacher's career[123]. From planning a single lesson to crafting a spiral curriculum for integrated STEM education, the complexity of these tasks requires a corresponding increase in curriculum design capacities. It is imperative to acknowledge the diversity in teachers' capacities, matching their roles and responsibilities.

When teachers feel attracted to this kind of design-related career pathway, the crux of our endeavor lies in the quest regarding how teachers can further develop their curriculum design capacities[124]. To this end, we propose a combined approach[125]: learning *through* design and learning *about* design. *Learning through* design involves collaborative efforts, such as through teacher design teams (TDT), professional learning communities (PLC) and lesson study teams (LST). These endeavors, rooted in sociocultural theories, are characterized by three main elements: learning is mediated through design activity; learning is social in nature; and learning is situated and culturally embedded[126]. Simultaneously, teachers will also *learn about* the ingredients of design work, covering a rich knowledge base regarding the six underlying types of expertise essential for curriculum design. These design capacities, acquired via pre-service education and ongoing professional development, form the core for teachers who are opting to specialize in curriculum design.

In this respect, our Master of Science Education program at the TU/e teacher education institute sows the first seeds in the pedagogical content knowledge (in Dutch: 'vakdidactiek') courses where students learn to plan, execute and evaluate their lessons. Moreover, in the Educational Design Research course, students work in mixed teams on solving curriculum challenges brought in by schools in our regional networks. In this EDR course, students perform problem analyses and design and evaluate a variety of solutions in collaboration with representatives

[122] Priestley (2019)
[123] Earlier prototypes of this framework can be found in Nieveen & Van der Hoeven (2010); De Vries, Nieveen & Huizinga (2020)
[124] Also referring to Stenhouse's (1975) well-known aphorism "there can be no curriculum development without teacher development."
[125] Van Veen, Zwart, Meirink & Verloop (2010)
[126] cf. Pieters, Voogt & Paraja-Roblin (2019); Nieveen, Van den Akker, & Voogt (2023); Van den Akker & Nieveen, (2021)

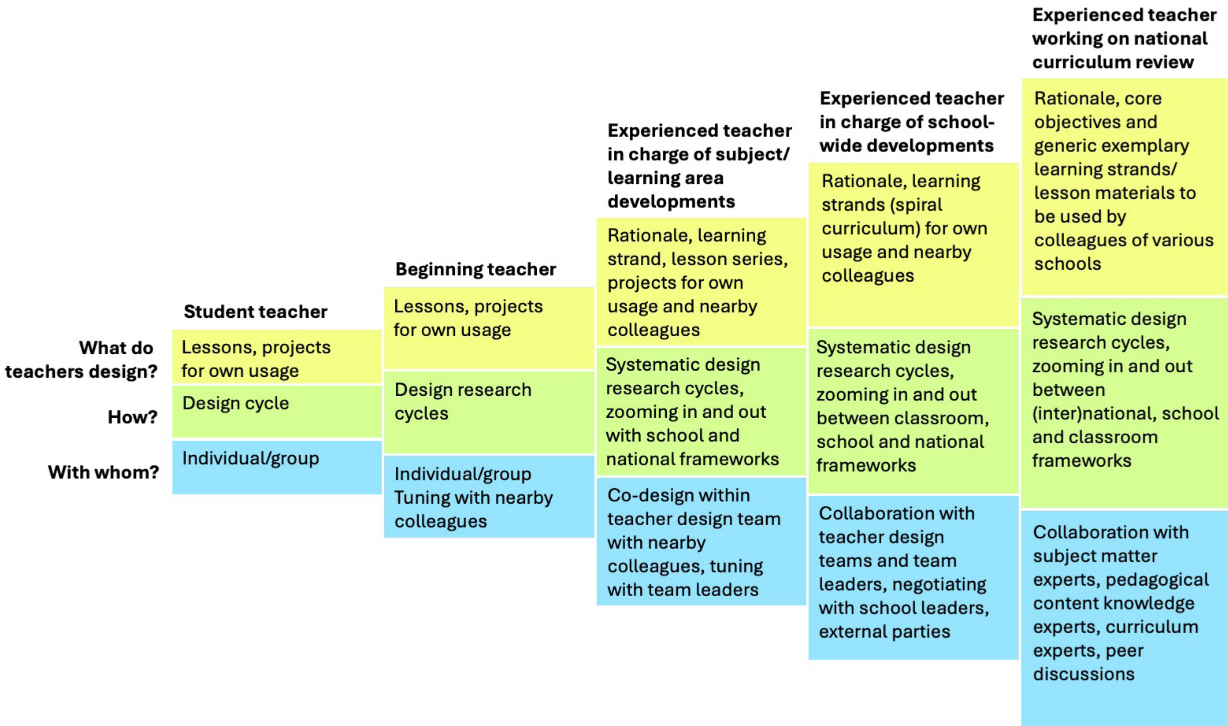

Figure 11. Example of diversification of curriculum design tasks

of the schools[127]. In this way, they extend their curriculum design expertise and get some first experiences as teacher designers in school settings. Moreover, an increasing number of students from other TU/e bachelor's programs indicate an interest in learning to design innovative lesson materials related to their fields of expertise. Eventually, these designers may become of significant help for in-school teacher design teams and might even become attracted to the teaching profession.

As we look to the future of innovative STEM education, the establishment of teacher career pathways for curriculum design capacities is essential. The recently granted National Growth Fund[128], emphasizing the creation of widely supported development/career pathways for teachers, is echoing our aspirations. Regional co-creation labs will play a pivotal role in understanding teachers' needs, designing professional development and enhancing the learning culture within schools. Sufficient time for design work and related professional development is a priority, even (or especially) in the event of teacher shortages, in order to increase the attractiveness of the teaching job.
In conclusion, our journey toward innovative STEM education requires a collective effort. Teachers, school leaders and educational stakeholders must unite in developing curricular design capacities. We are ready to continue our design research work regarding the curriculum design pathways for teachers together with others in this field and to co-design and evaluate professional development activities, from formal in-service education and workshops to informal mentoring and use of (computer-supported/AI-based) job aids[129]. The research chair 'Curriculum Design in STEM Education' stands ready to contribute to this cause, creating pathways towards a vibrant and sustainable educational landscape for STEM teachers and their students.

[127] cf. Plomp & Nieveen (2013); Mckenney & Reeves (2019); Thurlings et al, (2023)
[128] The National Growth Fund has been granted for the national approach of professional development of teachers (Nationale Aanpak Professionalisering Leraren, NAPL https://www.nationaalgroeifonds.nl/overzicht-lopende-projecten/thema-onderwijs/nationale-aanpak-professionalisering-van-leraren)
[129] cf. De Putter (2023); Nieveen (1997)

Our appreciation

Together, we would like to express our gratitude to the TU/e Executive Board for the opportunity they have given us and the trust they have placed in us.
Our sincerest thanks go to our colleagues across TU/e and, in particular, at the Department of Applied Physics and Science Education for their warm welcome and enthusiasm, which has led to so many fruitful collaborations. There is more to come, and we look forward to that.

Jan – Dear family, friends, colleagues and students, I very much appreciate your presence here today. Many thanks to my former University of Twente colleagues; it was a special time with many opportunities to develop myself. I enjoy every workday and I realize that this is very much related to working with my colleagues and students. My deceased father, Gerrit, a carpenter and later a teacher, was always of the opinion that I should go to a technical university. My mother, Berthy, I'm delighted that you are here today. You are always interested in what I'm doing and where I've been; thank you for everything. A special thank you to my dear partner Dieneke. Together with Hanne, Els, Felix, Berend and many others, we have had so many special moments. I hope to have many more with you all. ... Ik heb gezegd.

Nienke – Arriving here is the culmination of a journey that came with great companions. Many thanks to colleagues and students at the University of Twente, along with my mentors Jan van den Akker, Wilmad Kuiper and the late Tjeerd Plomp, and my first-hour study friends Annette Thijs, Susan McKenney and Irene Visscher-Voerman, as well as Gerdy ten Bruggencate. Thanks also to SLO colleagues, in particular Elvira Folmer and Maarten Pieters and members of curriculum networks and committees, especially Daniel Alvunger, Majella Dempsey, Stavroula Philippou and Mark Priestley. I express love and gratitude to my dear friends and family, particularly my mom Zwanet, who is here with her ever warm support, and my deceased dad Jan Marten, with whom I was able to share this new step. And lastly to my love Marcel and to our children Mirte, Melle and Arne, your love, perspectives and humor mean the world to me. I am eager for the wonderful times that lie ahead with all of you. ... Ik heb gezegd.

Esther – I would like to thank all my former colleagues and students at Universidad Simón Bolívar, the University of Manchester, Monash University and the University of Strathclyde, my research collaborators and the many students who were in my classrooms and volunteered to support my research. My deepest gratitude to my mentors, who have supported my personal and professional development, for being inspiring role models. I would also like to thank my friends for their incredible support and my family for their constant and unconditional love. It has been a great journey so far and you have all shaped it along the way. No doubt you will continue to do so. ... Ik heb gezegd.

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Curriculum Vitae

Prof.dr. Nienke Nieveen was appointed as a full professor of Curriculum Design in STEM Education on October 1, 2022.

Nienke Nieveen obtained her PhD in the curriculum design domain at the University of Twente in 1997 and became an assistant professor in Twente. From 2007 to 2019, she worked at the SLO Netherlands Institute for Curriculum Development and combined this with an associate professorship at TU/e. In 2019, she returned to the University of Twente as an associate professor and program director of the teacher education programs. In addition to the full professorship here in Eindhoven, she is the program director of the TU/e teacher education programs for the STEM subjects and is a member of the National Scientific Curriculum Committee, associate editor of The Curriculum Journal and Pedagogische Studien and chair of the Curriculum division of VOR (Dutch Educational Research Association). Her research focuses on curriculum design research and school-based curriculum development.

Prof.dr. Jan van der Veen was appointed as a full professor of Teacher Professional Development in Secondary & Higher STEM Education on February 1, 2021.

Jan van der Veen worked as a Physics teacher after graduating from the University of Groningen. He moved onto the University of Twente, focusing on e-learning and project-based learning, while finishing his PhD in 2001. He was one of the initiators of the 4TU Centre for Engineering Education. In 2019, he received a Comenius Leadership grant focusing on the design and implementation of interdisciplinary engineering education. Jan chairs the national Beta4all steering group, supporting the domain expertise of STEM teachers. At TU/e, he chairs the Eindhoven School of Education, working with many regional school partners. His focus is on the professional development of teachers and STEM research projects in secondary and higher education. He collaborates with international education career framework initiatives and recognition and rewards projects.

Prof.dr.ir. Esther Ventura-Medina was appointed as a full professor of Innovation in STEM education on November 1, 2022.

Esther Ventura-Medina obtained her PhD in Chemical Engineering from the University of Manchester in 2000, after which she completed a Postgraduate Certificate in Education in Secondary Mathematics. In 2005, she joined the Department of Chemical Engineering at the University of Manchester as a lecturer, supporting students' transition from secondary to higher education and introducing innovative approaches to teaching, such as enquiry and problem-based learning. Later, she worked as a senior lecturer at the universities of Monash and Strathclyde, introducing research-informed innovative education practice. Here at TU/e, she is a full professor at APSE-ESoE, the scientific director of the Academy for Learning and Teaching (ALT) and the lead in the 4TU Centre for Engineering Education. Her research focuses on student-centred learning approaches, including teamwork and digital learning.

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