Chapter 20
Interdisciplinary Research and Development—Opportunities and Challenges

Rae Earnshaw

Abstract Discipline boundaries have been systematically developed and established over the last century which reflect some of the perceived differences between the science and engineering disciplines and those in the arts and humanities. However, both internal and external factors can result in new disciplines which can arise at the boundaries between existing disciplines, rather than within them, and may combine different aspects of these disciplines. Some of these may be produced by external drivers such as information technology, the Internet and Big Data. It has been argued that innovative and creative approaches that cross disciplinary boundaries are more effective in producing new information and new knowledge. The current scope and priority of interdisciplinary research can be obtained by analyzing the funding programmes of national and international bodies and agencies. Some funding programmes are looking for quicker and more effective solutions for complex grand challenge problems. Analyses of complex information systems may require the crossing of departmental boundaries in order to generate new knowledge. It is recognized that obstacles to effective and sustained interdisciplinary collaborations have the potential to arise unexpectedly. Also, social and cultural factors often come into play when new initiatives are proposed. Mechanisms to grow interdisciplinary research such as internal funding, networking, and training are considered. Potential barriers to progress are also noted. Ongoing issues that remain to be addressed are summarized.

Keywords Discipline domains · Collaboration · Creative approaches · Cultural factors · External drivers · Complex information systems · Research metrics

R. Earnshaw (✉)
Department of Computer Science, Faculty of Engineering and Informatics, University of Bradford, Bradford, UK
e-mail: r.a.earnshaw@bradford.ac.uk

St John's College, Durham University, Durham, UK

Faculty of Art, Science and Technology, Wrexham Glyndŵr University, Wrexham, UK

R. Earnshaw et al. (eds.), *Technology, Design and the Arts—Opportunities and Challenges*, Springer Series on Cultural Computing, https://doi.org/10.1007/978-3-030-42097-0_20

20.1 Introduction

In 1959 Snow identified differences between the science and engineering disciplines and those in the arts and humanities [1]. This appeared to be due to a variety of factors including tradition, vocabulary, ways of working, and contributions to society, all of which could be different in different disciplines and circumstances.

Critchley [2] proposed that Snow had diagnosed the emergence of two cultures because of the loss of a common framework of understanding. Scientists and engineers favoured advancement of society through technology and industry, whereas the arts and humanities preferred intellectual and literary endeavour.

However, Gould took an opposing point of view and emphasized the commonalities between science and the humanities [3]. In 1963, Snow appeared to take a more optimistic view about the relationship between science and arts [4].

These views stem from an era when 5% or less of the population participated in higher education, and a faculty member's role was not subject to detailed performance management controls by their institution. The freedom in the academy provided ample opportunity for new ideas to be developed and explored. Research grants were relatively easy to obtain (there were fewer applicants), and there was opportunity for regular publication of research results in refereed journals or monographs. Discipline boundaries had been fairly systematically developed and established over the previous century and these were generally respected. In addition, there was ample new knowledge to be discovered within the existing discipline domains.

This chapter provides a landscape view of interdisciplinary research and development and examines the areas where future progress may be made. The ways in which the creative arts relate to this view are detailed in Sect. 20.6 of this chapter.

20.2 Development of New Disciplines

However, in the last half-century new disciplines have arisen and there has been an acceleration of the pace of change. For example, computer science developed principally out of mathematics in the UK because of the associated interests in numerical analysis and the requirement to use automated methods to perform the required calculations. In the USA, computer science developed principally out of engineering due to the interests in hardware and manufacturing computing devices. However, before they emerged as separate academic disciplines with their own departments and faculty members, they did exist along the boundary of the existing disciplines of mathematics and engineering, respectively. The primary driver for the development of computer science came from outside the academy in the form of the vacuum tube computer (1940) [5], the transistor (1948) [6], and the silicon chip (1961) [7]. National governments appreciated the strategic significance of the technology not just for scientific and business computation but also for their application to a wide variety of disciplines and problems, and so invested significantly in computing facilities for the academy and national research laboratories. Shockley, Bardeen, and Brattain were jointly awarded the Nobel Prize in physics in 1956 [8] for the development of the transistor. Therefore, in its initial stages, computing was seen as part of the natural sciences, at least in its hardware aspects. This is still the case with regard to quantum computing, and publications from this area can appear in the journal Nature [9], whereas those from other areas of computer science do not.

Therefore, new disciplines can arise at the boundaries between existing disciplines, rather than within them, and may combine different aspects of these disciplines. Oceanography is a further example of an interdisciplinary discipline as it covers all aspects with respect to the ocean, which includes its natural components (seawater, living creatures, and the sea bed); its currents and movements (fluid dynamics); and modelling of the overall system (such as by finite element analysis). Similarly, cognitive science draws on interdisciplinary aspects of psychology, linguistics, philosophy, interaction, and computer analysis.

Shneiderman [10] details how innovative and creative approaches that cross disciplinary boundaries are more effective in producing new knowledge. In particular, he advances the case for combining applied and basic research and a new paradigm for interdisciplinary collaboration that puts engineering and design on an equal footing with basic science. Thus even within well-established disciplines there are significant opportunities for new approaches.

Pressures on funding of universities in recent years have resulted in competition between departments and between institutions. There is competition between departments for students and competition between institutions for research funding and league table positions. It also produced competition between disciplines that resulted in science and engineering arguing that they were better for students and society because they imparted skills and generated jobs, whilst arts and humanities subjects were less useful in these respects. In some cases, it resulted in national bodies advising students against studying arts subjects, which in turn forced some of these academic departments to close because their institutions could no longer afford them if they could not pay their way. Senior academics argued strongly for the value of arts and humanities [11, 12]. However, this overall antipathy between arts and sciences which has been somewhat artificially created has in some cases acted against furthering the important collaborations that are needed. Therefore obstacles to effective and sustained interdisciplinary collaborations have the potential to arise unexpectedly. The participants need to have the perspectives and resources to be able to deal with them.

Further information on the advantages and disadvantages of interdisciplinary research are detailed in [13].

20.3 Acceleration of the Pace of Change

Friedman [14] identifies three principal components that are accelerating change

(i) Market
(ii) Nature
(iii) Technology

The market includes the effects of globalization and political tribalism. Nature includes climate change. Technology includes the Internet and the increasing power and reducing costs of computational facilities. All of these act as powerful forces and they act in parallel. Their combined effect can cause severe disruption. Society needs to be able to adapt and respond to the changes that these forces represent. Many disciplines and applications use the Internet as a delivery service, to access Cloud storage, a computational resource, or a marketing medium, and therefore become subject to its accelerating effects. One Internet year is said to be equivalent to seven calendar years [15]. One effect of the Internet has been to break down traditional barriers. Formerly research teams were co-located with their departments, but today the Internet can be used to facilitate collaboration across departments and countries with equal facility. This can result in a greater sharing of ideas and results. Therefore the potential for interdisciplinary collaboration is substantial, and the Internet can act as an external driver of change in the same way that the silicon chip inaugurated the computer revolution.

Many institutions and organizations are increasingly recognizing the need to analyze large data sets. This can arise in the context of experiments, sensors, simulations, and the user data gathered by social sciences and social media companies. In the academy, such data is often concentrated in a centralized Data Center, with associated expertise on hand to advise on data collection and data analysis. They are often resourced centrally by the academy as they are regarded as an investment to support all disciplines. Such central resources also offer graduate courses (e.g., Masters, Ph.D.) in the various areas of Big Data and its applications. Thus, Data Centers can have the direct effect of encouraging and facilitating cross-disciplinary collaborations. Therefore, the rise of Big Data, rather like the rise of the Internet, has become a significant internal and external driver which forces researchers involved in this area towards interdisciplinary collaborations.

It is clear that interdisciplinary working is not just a matter of the right structures and appropriate facilitation. Social and cultural factors also come into play [16].

20.4 Interdisciplinary Research Funding and Research Priorities

An indication of the scope and priority of interdisciplinary research (IDR) can be obtained by analyzing the funding programmes of national and international bodies and agencies. Included in this analysis are the National Science Foundation (NSF) in the USA, the European Union, and the UK funding agencies.

20.4.1 National Science Foundation (NSF)

NSF states the priority it gives to interdisciplinary research in terms of advancing scientific discovery and extending the fields of knowledge [17–19]. It also supports interdisciplinary training in order to enable the recipients to be able to address current problems in innovative ways [17, 18].

The following challenges were identified [18]:

- Collaboration across people with different backgrounds and cultures
- Extra time needed to build consensus and learning new methods
- Traditions and policies tend to allocate resources to traditional areas
- Professional societies could assist more by active support of interdisciplinarity
- Ensure the peer review process including interdisciplinary researchers.

Potential lessons from industry and national laboratories were as follows [18]:

- Industrial and national laboratories are generally organized to address the problems
- Management is more top-down than in the academy
- There is potential for greater collaboration between the academy and industry.

20.4.2 European Union

A report to the European Union (EU) on interdisciplinary research in the context of ERA and Horizon 2020 identified a number of reasons why this should be a priority. This included the following [20]:

- Faster solutions are needed for grand challenge problems
- Engage in problem-driven approaches
- Exploit disruptive innovation
- Bridge the gap between research communities.

The report also outlined the potential effects of interdisciplinary research [20]:

- Trigger innovation
- Add value to the disciplines
- Solve complex real-life problems
- Bring about discoveries outside traditional disciplines
- Change established research perspectives and paradigms
- Achieve impact.

The following enablers were identified for interdisciplinary research and development [20]:

- Resourcing of people, time, and space
- Providing targeted funding
- Developing interdisciplinary skills and practices
- Triggering of appropriate social and cognitive dynamics between researchers
- Ensuring undergraduate students receive a grounding in different disciplines
- Facilitating an understanding of different scientific vernaculars.

The EU has also explored the reasons for the support of interdisciplinary research in disruptive technologies [21].

20.4.3 UK

Research England was set up as a Council of UK Research and Innovation by the Higher Education and Research Act 2017 [22]. It exists and alongside the other existing Councils (the seven Research Councils [23] and Innovate UK [24]). One of its functions is to evaluate the extent to which interdisciplinary research and development. It includes including cross-disciplinary, multi-disciplinary, interdisciplinary and transdisciplinary activity.

A number of reports on interdisciplinary research (IDR) have been undertaken by various bodies in the UK. Each body has particular interests to do with their mission, so each report is oriented to their objectives. However, taken together the reports

- highlight a range of barriers and incentives for interdisciplinary research (IDR) in the UK
- explore the challenges associated with assessing interdisciplinary research
- provide some real-world examples of ‘what works’ in supporting an IDR culture in today’s higher education research institutions [25].

These are now summarized.

20.4.3.1 The British Academy

The Executive Summary of 'Crossing paths: Interdisciplinary institutions, careers, education and applications' by the British Academy noted the following [26]

- Requests for evidence identified a broad support of interdisciplinary research
- Essential for addressing complex problems and global social challenges
- Enhances understanding of the separate disciplines.

20.4.3.2 Global Research Council

A Survey Report for the Global Research Council (GRC) in 2016 noted the role and importance of IDR, the right conditions for establishing interdisciplinary working; assessment, evaluation, and measurement; careers, training, and recognition; and produced a number of recommendations including the following [27]:

- Better sharing of best practice
- The identification of grand challenge problems
- The provision of funding support over adequate time frames
- The provision of physical and social space
- Fair review processes
- Appropriate end of project evaluation metrics
- Training and capacity building
- Improving awareness of the value and importance of IDR.

20.4.3.3 Review of the UK's Interdisciplinary Research

A review of the UK's interdisciplinary research using a citation-based approach was undertaken for HEFCE and MRC by Elsevier. In order to assess interdisciplinarity, the diversity of article bibliographies was studied in eight comparator countries for the period 2009–13. The principal conclusions were that interdisciplinary activity was growing in the UK; it has an international collaboration component, and the academy was a principal contributor [28]. It also noted a lower citation impact for interdisciplinary research.

20.4.3.4 Landscape Review

A landscape review of interdisciplinary research in the UK identified some potential areas where new stakeholders could promote suitable conditions for interdisciplinary research to develop [29].

20.4.3.5 Case Study Review of English Higher Education Institutions (HEIs)

A Case Study review by Technopolis identified a number of ways of organizing IDR such as [29]

- *Co-location of researchers*
- *Researcher networks across subject areas, departments or faculties*
- *Researcher-led ('bottom-up') and/or strategic institutional ('top-down') approaches*
- *A thematic or generic focus for IDR*
- *Support for high-quality research in general, not specifically for IDR.*

It also suggested ways of growing IDR such as seed corn funding, networking events, improving the skills base by appropriate Masters courses and Ph.D. programmes [29].

20.4.3.6 Team Science in Biomedical Research

A report to the Academy of Medical Sciences in 2016 summarized the characteristics of team science including benefits and challenges, reward and recognition, and career progression [30].

An assessment of progress was done in 2019 [31].

20.4.3.7 Arts and Humanities Research Council

The Global Challenges Research Fund (GCRF) is a 5-year £1.5bn fund and a key component in the delivery of the UK Aid Strategy: tackling global challenges in the national interest. The funding was for 1 December 2018 onwards [32]. The objective includes interdisciplinary research excellence.

20.5 Interdisciplinary Research and Development in the Creative Arts

20.5.1 Introduction

The continued increase of processing power, data storage, telecommunications bandwidth, and display screen resolution provide greater opportunities for handling new types of users and applications. It also increases the ubiquity and facility of computational devices in terms of mobility and user interfaces, whether utilized directly by designers, audiences, users, or embedded in the application environment.

Art and design have a long history in antiquity. They have shaped the values, social structures, communications, and the culture of communities and civilizations. The direct involvement of artists and designers with their creative works has left a legacy enabling subsequent generations to understand more about their skills, their motivations, and their relationship to the wider world, and to see it from a variety of perspectives. This in turn causes the viewers of their works to reflect upon their meaning for today and the lasting value and implications of what has been created.

Some historical examples of art and design were able to use semi-automated methods for creation, particularly where large areas of a canvas or model needed to be filled in. However, it was only with the advent of modern technology that the advantages of harnessing digital techniques were able to be exploited. One of the earliest examples was the Architecture Machine [33] designed and implemented at the Massachusetts Institute of Technology (MIT). The objective was to enable digital technology to assist the user with design tasks, particularly those at large and small scales, where it was known that designers had particular challenges and difficulties. In addition, the computer was able to store data and reproduce designs, thus facilitating the speed-up of the iterative process towards a final design which met the objectives of the designer and the requirements of the client [34]. It also enabled the aesthetics of the design to be seen at the design stage within the wider content of the environment in which it was to be placed. This was subsequently extended using virtual reality technology to enable prospective users of the building to perform 'walk-throughs' within the created space and understand how it would work in practice in terms of logistics, to ensure it was fit for the purpose. Materials and implementation costs could also be optimized at the design stage.

More recent examples of artists and designers interacting with technology include the use of the iPad to produce sketches of scenes which were subsequently grouped into a montage to give a large wall display containing multiple images [35]. Mobile phones with high-resolution screens are being used to produce art works and communicate them via social media networks [36]. Art installations have also harnessed modern technology both to process information and to display it. Such environments have proved useful in engaging users and visitors with real-time images and interactive art.

Collaborative design has enabled the sharing of information across digital networks to produce designed objects in virtual spaces. Augmented and virtual reality techniques can be used to preview designs before they are finalized and implemented. Ancient and modern art and design environments illustrate the design and implementation processes involved, and the opportunities for collaborating and interacting with other artists and designers.

There are also increasing opportunities for artists to use their skills and expertise to illuminate the latest discoveries in science and technology [37, 38]. There is increasing interest in extracting meaning from very large data sets, which in turn requires effective methods of analysis and presentation of the results. Science and technology are also able to contribute increasingly to the arts, either as a component of the artistic output, or part of the methodology used to produce the output. In addition, the traditional boundaries between arts and technology are becoming blurred due to the way computing technology is being embedded into the everyday environment in a seamless way, and the use of social media which enables a greater degree of involvement and sharing by the community. Social media can open up new dimensions of interaction and participation in both the arts and the sciences [34].

20.5.2 Contributions of Technology to the Creative Arts

Technology contributes to the creative arts by providing tools, interfaces, facilities for collaboration, access to data, as well as a range of software for a variety of applications. Such facilities may also include artificial intelligence and machine learning techniques. Telecommunication networks enable artists to participate in communities and collaborate with other artists on joint projects. Exhibitions can be displayed on the Internet and allow local and remote audiences to participate and interact with the project and each other. Such environments can also be used for a variety of applications including simulation, planning, theatre rehearsal, and entertainment, such as computer games [39–42]. Excellent artistic skills are important for the generation of the scenes for effective gameplay.

Artistic works may use digital methods to produce digital art [43]. Computer games may be considered as a particular kind of digital art as they use computer technology and associated software to produce the game.

20.5.3 Contributions of the Creative Arts to Technology

The creative arts have made contributions to Renaissance Teams, the design of technology, and the effective incorporation of technology into the wider environment. Artists have been able to contribute to scientific analysis and enable new results to be produced [44, 45]. Such Renaissance Teams can stimulate creativity and produce new knowledge [46] in way that would be very difficult, if not impossible, for a single artist to do on their own. SciArt is a term used to describe the artistic contributions that can be made to scientific investigations [47].

Technology companies give increasing attention to the aesthetics, usability, and engagement of the devices that they create (e.g., Apple [48, 49]).

An example of the analysis of cultural artefacts by computer is the Digital Michelangelo Project at Stanford University [50, 51]. Its objectives were to advance the technology of 3D scanning and to create a long term digital archive of significant cultural artefacts in Italy. These archives were made generally available over the Internet.

20.6 Methodologies for Identification and Assessment of Research

A number of methods to evaluate research are being used by institutions and national bodies. These include journal quality (such as by impact factor and internationality), paper citation rates, impact factors, H-indices of the individuals and departments, and altmetrics. The UK Research Excellence Framework (REF) also has international representation on its evaluation panels in order to provide externality, and to seek to align internal review processes with externally accepted standards.

A number of difficulties and challenges arise in seeking to extend these methods of assessment within single disciplines to research delivery across a number of disciplines. Identification and assessment of interdisciplinary research are summarized in a consultancy report [52], which noted that different metrics can produce different results [53].

20.7 Conclusions

20.7.1 Ongoing Issues

Although interdisciplinary research has been identified as a priority by NSF, EU, and the UK, and resources have been identified to give grant and infrastructure support, the following ongoing issues remain to be fully addressed

(1) Strong discipline silos are still the norm in higher education and graduate research and there seems to be little inclination to change apart from a relatively small number of institutions such as Arizona State University [54–56] and Pohang University of Science and Technology (Postech) [57].
(2) External examiners who adjudicate on Ph.D. theses would not normally have interdisciplinary experience and expertise sufficient to give an appropriate and fair evaluation of an interdisciplinary thesis.
(3) Graduate students can feel that an interdisciplinary project may be too risky, and also may have an uncertain outcome.
(4) Budget structures in higher education are often ring-fenced around specific disciplines. It can also be difficult to allocate part of the budget across an internal boundary.
(5) Interdisciplinary research appears to be mainly stimulated by external drivers such as information requirements or technology developments. These drivers often require new ways of working. This results in interdisciplinary research operating in reactive mode rather than seeking to advance proactively according to a detailed agenda.

(6) Moving away from a traditional discipline into a new area can still be perceived as risky due to the inertia in the academy, the difficulty of applying research metrics to new areas, and uncertainty about the future of the new discipline.
(7) Increasing competition for grant funding and funding within institutions, can force review bodies to be more conservative and only allocate funding to well-established areas, when such funding is limited.

20.7.2 Enablers for Collaboration Between the Arts and the Sciences

Traversing the boundaries between disciplines can be a challenge. However, recent developments have brought about a number of enablers. Firstly, the Internet has provided a greater ease of communication across disciplines and between researchers. It has also flattened organizational hierarchies to some degree, which in turn has reduced the traditional barriers between existing disciplines. Secondly, the model of Renaissance Teams [58] has proved useful in bringing together interdisciplinary groups of researchers with complementary expertise sets and defined goals. Thirdly, there have been significant successes in the application of information technology to the arts and humanities (for example, in the digitization of ancient manuscripts and artefacts). Fourthly, art and design have been successfully applied in support of the creative processes involved in generating new technology products and services, and in the presentation of scientific results. Fifthly, the increasing amounts of data being generated by research projects have resulted in the establishment of Data Science Centers within the academy, with teams of faculty and researchers brought together from various disciplines. Sixthly, grant funding bodies are increasingly focussing on larger initiatives often traversing different disciplines and countries (e.g., European Union grants) so require personnel to work together on advanced research and development. In addition, creative and artistic cooperation has demonstrated the benefits for all parties. All these factors make interdisciplinarity more the norm for the future and can generate a level of momentum and validity which provide reassurance and support for new researchers who wish to enter the area.

References

1. Snow, C.P.: The Two Cultures. Cambridge University Press, Cambridge, UK (1959)
2. Critchley, S.: Continental Philosophy: A Very Short Introduction, p. 49. Oxford University Press, Oxford, UK (2001)
3. Gould, S.J.: The Hedgehog, the Fox, and the Magister's Pox. Harmony Books, New York City, NY (2003)
4. Snow, C.P.: The Two Cultures: And a Second Look: An Expanded Version of The Two Cultures and the Scientific Revolution. Cambridge University Press, Cambridge, UK (1963)

5. https://www.webopedia.com/DidYouKnow/Hardware_Software/FiveGenerations.asp
6. https://www.cedmagic.com/history/transistor-1947.html
7. http://edition.cnn.com/2004/TECH/12/27/explorers.silicon/index.html
8. https://www.nobelprize.org/prizes/physics/1956/summary/
9. https://www.nature.com/authors/author_resources/about_npg.html
10. Shneiderman, B.: The New ABCs of Research: Achieving Breakthrough Collaborations, p. 336. Oxford University Press, Oxford, UK. ISBN 9780198758839 (2016)
11. https://www.timeshighereducation.com/opinion/a-dangerous-downgrade-undervaluing-the-arts
12. https://www.thebritishacademy.ac.uk/news/diversity-subjects-essential-national-prosperity-post-brexit-warns-british-academy
13. Earnshaw, R.A.: State of the Art in Digital Media and Applications, Chapter 3, pp. 21–28. Springer, Switzerland. ISBN: 978-3-319-61408-3 (2017). For more information see: http://www.springer.com/gb/book/9783319614083
14. Friedman, T.J.: Thank you for Being Late: An Optimists Guide to Thriving in the Age of Accelerations. Penguin, London (2017)
15. Clark. J.: Netscape Time, p. 262, St. Martin's Press, London (1999)
16. Bruns, P.: http://researchdevelopment.byu.edu/wp-content/uploads/2012/12/Full_Report_Creating_Interdisciplinary_Science.pdf
17. https://www.nsf.gov/od/oia/additional_resources/interdisciplinary_research/
18. Committee on Facilitating Interdisciplinary Research, Committee on Science, Engineering, and Public Policy.: Facilitating Interdisciplinary Research, p. 2. National Academies, National Academy Press, Washington (2004). https://www.nap.edu/read/11153/chapter/1#xxvi, https://www.nap.edu/catalog/11153/facilitating-interdisciplinary-research
19. https://www.nsf.gov/od/oia/additional_resources/interdisciplinary_research/definition.jsp
20. https://ec.europa.eu/research/openvision/pdf/rise/allmendinger-interdisciplinarity.pdf
21. https://ec.europa.eu/futurium/en/digital4science/why-should-interdisciplinary-high-risk-research-disruptive-technologies-be-supported
22. https://re.ukri.org/about-us/
23. https://www.ukri.org/about-us/our-councils/
24. https://www.gov.uk/government/organisations/innovate-uk
25. https://re.ukri.org/research/interdisciplinary-research/
26. https://www.thebritishacademy.ac.uk/interdisciplinarity
27. https://www.globalresearchcouncil.org/fileadmin/documents/GRC_Publications/Interdisciplinarity_Report_for_GRC_DJS_Research.pdf
28. https://webarchive.nationalarchives.gov.uk/20170712122715/, http://www.hefce.ac.uk/pubs/rereports/Year/2015/interdisc/
29. https://webarchive.nationalarchives.gov.uk/20170712122426/, http://www.hefce.ac.uk/pubs/rereports/year/2016/interdis/
30. https://acmedsci.ac.uk/policy/policy-projects/team-science
31. https://acmedsci.ac.uk/file-download/52394024
32. https://ahrc.ukri.org/funding/apply-for-funding/archived-opportunities/gcrf-interdisciplinary-research-hubs/
33. Negroponte, N.: Toward a theory of architecture machines. J. Arch. Educ., March (1969)
34. Earnshaw, R.A.: Art. Design and Technology. Springer. ISBN: 978–3-319-58120-0 (2017). https://www.springer.com/gb/book/9783319581200
35. How David Hockney became the World's foremost iPad Painter, Wired. https://www.wired.com/2013/11/hockney/
36. https://en.wikipedia.org/wiki/Coldwar_Steve
37. Miller, A.I.: Colliding Worlds: How Cutting-Edge Science is Redefining Contemporary Art. W. W. Norton and Company (2014)
38. Wilson, S.: Art + Science Now: How Scientific Research and Technological Innovation are becoming key to 21st Century Aesthetics. Thames & Hudson (2012)
39. Virtual Amusement Park (VPARK). http://cordis.europa.eu/project/rcn/46555_en.html

40. Joslin, C., Molet, T., Magnenat-Thalmann, N., Esmerado, J., Thalmann, D., Palmer, I.J., Chilton N., Earnshaw, R.A.: Sharing Attractions on the Net with VPARK. IEEE Comput. Graph. Appl. IEEE Computer Society **21**(1), 61–71 (2001). https://doi.org/10.1109/38.895134
41. Virtual Interactive Studio Television Application using networked graphical supercomputers (VISTA). http://cordis.europa.eu/project/rcn/32297_en.html
42. Flerackers, C., Earnshaw, R.A., Vanischem, G., Van Reeth, F., Alsema, F.: Creating broadcast interactive drama in a networked virtual environment. IEEE Comput. Graphics Appl. **21**(1), 56–60 (2001). https://doi.org/10.1109/38.895133
43. https://en.wikipedia.org/wiki/Digital_art
44. Cox, D.J.: Using the supercomputer to visualize higher dimensions: an artist's contribution to scientific visualization. Leonardo **41**(4), 391–400 (2008)
45. Cox, D.J: Collaborations in art/science: Renaissance teams. J. Biocommun. **18**(2):15–24 (1991). https://www.ncbi.nlm.nih.gov/pubmed/1874707, https://muse.jhu.edu/article/243508, http://www.leonardo.info/isast/articles/popper.html, http://link.springer.com/chapter/10.1007%2F978-3-642-46954-1_28, https://datascience.lanl.gov/data/papers/Pursuing.pdf
46. http://swiki.cs.colorado.edu/CreativeIT/248.print
47. http://cargocollective.com/artscienceclimatechange/SciArt-The-confluence-of-art-and-science-in-conveying-the-uncertaintie
48. Yan, J.: Analysis of apple equipment in the product design thinking. In: International Conference on Advances in Management, Arts and Humanities Science (AMAHS 2016), Atlantis Press, 2016 (Open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/))
49. https://www.fastcompany.com/1665375/the-6-pillars-of-steve-jobss-design-philosophy, https://innovationmanagement.se/2017/06/22/lessons-from-apple-on-why-aesthetic-innovation-is-important/, https://www.cleverism.com/apple-product-design/
50. https://graphics.stanford.edu/papers/dmich-sig00/dmich-sig00-nogamma-comp-low.pdf
51. https://graphics.stanford.edu/projects/mich/
52. https://www.digital-science.com/resources/digital-research-reports/interdisciplinary-research-methodologies-identification-assessment/
53. https://digitalscience.figshare.com/articles/Digital_Research_Report_Interdisciplinary_Research_-_Methodologies_for_Identification_and_Assessment/4270289
54. Crow, M.M., Dabars, W.B.: Designing the New American University, p. 360. Johns Hopkins University Press, Baltimore, MD (2015)
55. https://newamericanuniversity.asu.edu/
56. Crow, M.M., Dabars, W.B.: Interdisciplinarity as a design problem: toward mutual intelligibility among academic disciplines in the American research university. In: O'Rourke, M.R., Crowley, S.J., Eigenbrode, S.D., Wulfhorst, J.D. (eds.) Enhancing Communication and Collaboration in Interdisciplinary Research, pp. 294–322. Sage Publications, Los Angeles (2013). http://methods.sagepub.com/book/enhancing-communication-collaboration-id-research, http://wwwhome.postech.ac.kr/web/eng/ecad_01_11
57. http://wwwhome.postech.ac.kr/web/eng/etc_01?p_p_id=EXT_BBS&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_EXT_BBS_struts_action=%2Fext%2Fbbs%2Fview_message&_EXT_BBS_messageId=14790
58. Cox, D.J: Collaborations in art/science: Renaissance teams. J. Biocommun. **18**(2), 15–24 (1991). https://www.ncbi.nlm.nih.gov/pubmed/1874707

Further Reading

59. Sharp, P.A., Cooney, C.L., Kastner, M.A., Lees, J., Sassisekharan, R., Yaffe, M.B., Bhatia, S.N., Jacks, T.E., Lauffenburger, D.A., Langer, R., et al.: The Third Revolution: The Convergence of the Life Sciences, Physical Sciences, and Engineering, p. 34. Massachusetts Institute of Technology, Washington, DC (2011)

60. Frodeman, R., Klein, J.T., Mitchum, C.: The Oxford Handbook of Interdisciplinarity. Oxford University Press, New York, USA (2010)
61. Hage, J., Meeus, M.T.H.: Innovation, Science, and Institutional Change Oxford. Oxford University Press, New York (2006)
62. Holley, K.A.: Understanding interdisciplinary challenges and opportunities in higher education. In: Ward, K., Wolf-Wendel, L. (eds.) ASHE Higher Education Report, pp. 1–131. Jossey-Bass; Wiley Periodicals, San Francisco, CA (2009)
63. Klein, J.T.: Creating Interdisciplinary Campus Cultures: A Model for Strength and Sustainability. Jossey-Bass, San Francisco (2010)