Design Course

Human Machine Interaction Design

Introduction to Operator Interface/Experience (OI/OX)

by
Vivek Kant
IDC, IIT Bombay

Source:
https://www.dsource.in/course/human-machine-interaction-design

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Introduction

The aim of this course is to present an advanced primer for design for operator experience in complex technological systems. The course derives from the field of study known as Human Factors. Specifically, it derives from a sub-field known as Cognitive Systems Engineering, Cognitive Engineering or Cognitive Human Factors. The goal of this subfield is to support humans in cognitive tasks and capabilities while interacting with technological systems. Within this sub-field there is an important direction towards appropriate interaction design for humans, such as operators, in complex technological systems. Oftentimes, the design for operator experience is also categorized under the label of Human Machine Interaction (HMI) design; however, HMI is more appropriately a part of the broader discipline of Human Factors (Cognitive Human Factors/ Cognitive Systems Engineering).One particular thread of research in this area was specifically devoted to the design for operators in safety-critical sectors, such as nuclear. Later the frameworks and ideas were extended to broader sectors to include oil and gas, defence and aviation, among others. This approach to design has been developed significantly by a number of researchers in human factors in the last few decades. In this tutorial, design of interfaces in complex technological systems will be outlined briefly deriving from a few major texts and papers in this area that have been listed in the bibliography for further reading. Thus, this advanced primer serves as an invitation to explore the field of interaction design for complex systems.

In order to design for operator experience in complex systems, certain design processes and frameworks have been developed by human factors researchers, practitioners and designers working in the area of complex systems. The tutorial begins with Section 1 presenting a case study of poorly designed interfaces in healthcare that actually caused deaths. This section also presents a cautionary note on the need to design proper interfaces for engineered systems and sets the basis of the rest of the primer. The tutorial continues with listing out the challenges of interaction design in complex systems in section 2. It then provides a brief historical outline of human factors, and interfaces in complex systems in Section 3. In section 4, the steps for the design of interfaces have been outlined. The tutorial concludes with a bibliography that is the basis of the ideas, processes and methodologies expressed in the tutorial. It also serves for pointing the way forward for readers who wish to explore this area in greater detail.

Learning Objectives

By the end of this primer, you will be able to,

a) Recognize the challenges involved in designing for operator experience in complex technological systems.

b) Identify the need for a structured design process to support humans in the operation of complex technological systems.

c) Use the design concepts and processes for designing for operator experience in complex technological systems.

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Poorly Designed Interfaces Kill People

Poor interface design can kill people! In this section, we introduce a case study of Therac-25 which highlights such a scenario. Therac-25 was a computerized radiation therapy machine, devised by Atomic Energy of Canada Limited (AECL), with one of the most dangerous human interface design and software related accidents. In this discussion of the case study, we will focus on the interface problems. The material discussed here has been gathered from three main sources described in the further readings section: Casey (1993); Leveson and Turner (1993) and Leveson (2017). The ones reading the primer are requested to consider these three documents for detailed understanding of all aspects of the accidents in Therac-25 case.

AECL and CGR, a French company collaborated to build medical linear accelerators that accelerate electron beams that could destroy tumours with minimal impact on the surrounding healthy tissues. Although AECL developed a radically new "double-pass" concept of electron acceleration in the 1970's, AECL and CGR's business relationship faltered. AECL started to build its own radiotherapy machine with their newly developed concept. This new technology was beneficial as it reduced the amount of space and energy required. Therac-25 was built on this new concept.

Therac-25 was a dual-mode linear accelerator that could deliver photons at 25 MeV or electrons at various energy levels. Therac-25 is more compact, more versatile and easier to use. The machine took advantage of the "depth dose" phenomenon allowing it precise localized aim at malignant tissue. The machine was designed to take advantage of the computer control from the outset and not be a stand-alone machine. It relied more on the software for the functions, and the computer's ability to control and monitor the hardware safety mechanisms and interlocks.

Although the machine was based and inspired from machines that had a history of clinical use but its past was without computer control. It also contained the industry-standard hardware safety features and interlocks which were manually controlled instead of letting the computer take over the control. With change in technology and growth of computers, the team behind Therac-25 put more faith on the software than on hardware reliability. The first hardwired prototype was produced in 1976 and a completely operational computerised commercial version was made available in late 1982. In March of 1983, a safety analysis was performed by the AECL in the form of a fault tree but apparently excluded the ones related to software and human interaction.

Operator Interface:
Therac-25 was operated through a DEC VT100 terminal. The operator would position the patient on the treatment table, and manually set the treatment field size, and gantry rotation, among other requirements. The operator then had to enter the patient identification, treatment prescription-mode, energy level, dose, dose rate and time, field sizing, gantry rotation and accessory data through the VT100 console.

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The system would then compare the manually set values with those entered into the console, and if it did match, a "verified" message would display permitting the system to treat. If it did not match, treatment would not proceed until corrected. These steps took a long time. Not surprisingly, the operators grumbled about this initially. Therefore, to accommodate this issue, the manufacturer made a provision by which instead of re-entering the data at the keyboard, a quick series of carriage returns was used to merely copy the treatment site data. This interface modification came into sharp relief in several of the accidents.

During operation, in case of an error, the machine was designed to shut down in two ways – first, a treatment suspend which required the system to be reset in order for it to restart; second, a treatment pause which required a single-key command to restart. The treatment pause could be resumed with the "P" key to proceed with the treatment. This feature could be invoked a maximum of five times, after which the machine would automatically stop the treatment and the operator had to reset the system.

The messages related to any error in the system were quite cryptic. For example, the word "malfunction" followed by a number: "Malfunction 54". In many of such cases, the operator could not refer to the manual as such scenarios were either not properly documented or provided no explanation. The operator did not have any knowledge about the fact that the malfunction messages were placing the patients under possibilities of harm. Further, Therac-25 did not have any in-built safety system that could prevent over-dosage caused by incorrect parameters being entered or intermixed.

In many cases, the operators explained that they had become immune to the error messages because they did not think that these were hampering patients' safety. In most cases, when the malfunctions occurred, either the service technicians or the hospital physicist would make the Therac-25 operable again.

Messages regarding low dose rate, V-tilt, H-tilt and many other issues, were quite normal during operation. Further, when the operators were instructed about the capabilities of the machine, they were given to understand that the machine had "many safety mechanisms" that would make it "virtually impossible" to overdose the patients. In their minds, the operators were convinced about the safety of the system.

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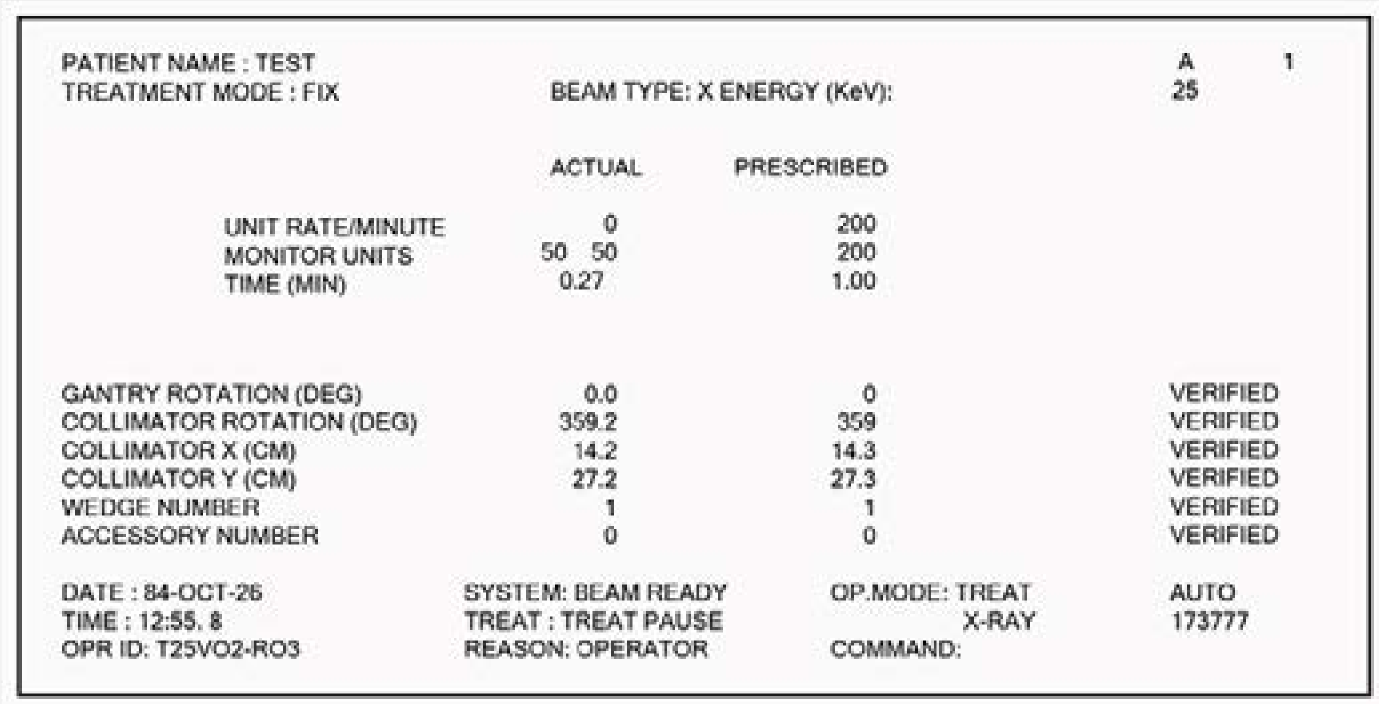

Operator Interface of Therac-25. Recreated from Leveson and Turner (1993).

Therac-25 Accidents:

AECL had eleven Therac-25 installed machines - five in US and six in Canada. There were a total of six reported accidents between 1985-87. Due to the accidents, the machine was recalled in 1987 for extensive design changes—hardware and software. We list, below, in a chronological manner the accidents that resulted in deaths and considerable injuries due to Therac-25. Amongst these, one accident (East Texas Cancer Centre, March 1986) has been developed in some detail to understand the functioning of the interface and its role in the accident.

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Map of accident sites of Thearc-25 between 1985-1987.

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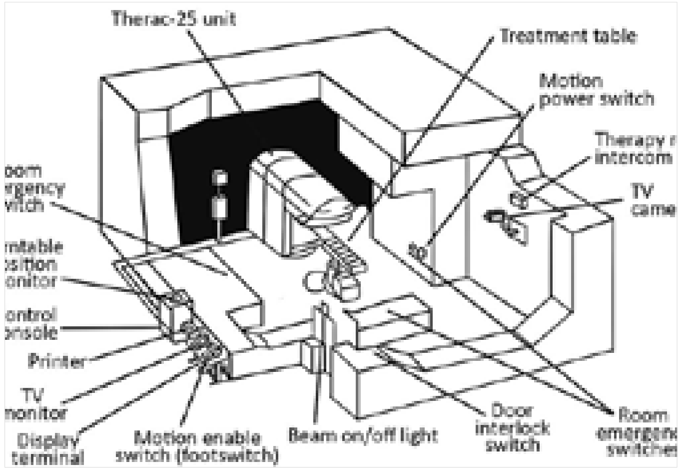
a. Kennestone Regional Oncology Centre, 1985: A 61 year old woman had undergone lumpectomy to remove a malignant breast tumour and was receiving follow-up radiation therapy to nearby lymph nodes. Due to Therac-25 malfunctions, the patient's breasts had to be removed because of the radiation burns and she lost the use of her shoulder and arm. The manufacturer and operators refused to believe that an accident of this magnitude could be caused by the machine!

b. Ontario Cancer Foundation, 1985: On July 26th, 1985, a 40 year old patient who was being treated for carcinoma of the cervix treatment but the machine shut down after only five minutes of activation with an "H-tilt" error message. The display at the time read "no dose" but indicated a "treatment pause". Due to poorly designed messages, interface problems as well as general technical problems of Therac-25, the AECL technicians estimated that the patient had received a very heavy radiation exposure (about 13,000 to 17,000 rads).

c. Yakima Valley Memorial Hospital, 1985: On December 1985, a woman who had come in for treatment with Therac-25 resulted in erythema, a condition of excessive reddening of the skin in parallel stripes on her right hip. She continued her Therac-25 based treatment because the cause of the reaction on her skin was not determined. Much later, when Therac-25 issues were brought to light, it was discovered that the patient had suffered from chronic skin ulcer, tissue necrosis under the skin and had been in constant pain ever since. these symptoms were relieved when the tissues were surgically repaired and skin grafts were made. The patient survived but was faced with minor disabilities and some scars.

d. East Texas Cancer Centre, March 1986: Therac-25 had been in use at the centre for two years without any accidents. More than 500 patients had been treated until then with that machine. It is the only accident with much more details than the others due to the diligence of the hospital physicist, Fritz Hager, whose efforts helped in understanding the problems of the machine.



Therac-25. Redrawn from Leveson and Turner (1993). Notice the control computer outside of the patient room. The operator had a view inside the treatment room through a TV camera and an intercom. The operator interface shown above.

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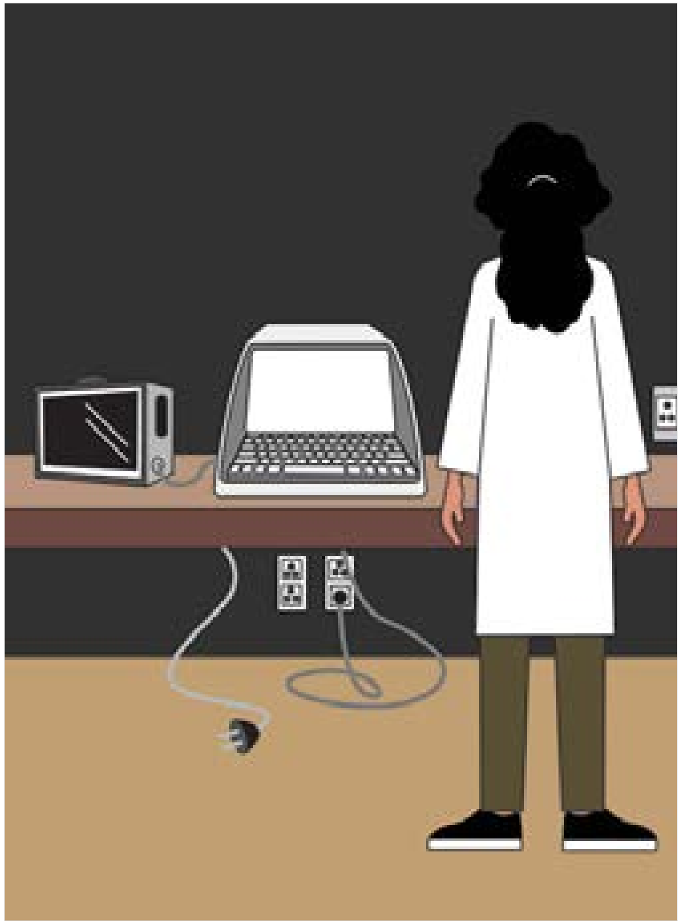
On March 21st, 1986, Voyne Roy Cox received follow-up radiation therapy for a tumour surgery. He was to receive the therapy at the back of his left shoulder. The technician, Mary Beth, helped him take position on the table. He was supposed to receive a treatment of 22 MeV electron beams of 180 rads.

Cox was used to watching Mary Beth operate the hand-held control console that rotated the table and him to the proper position underneath the machine's gantry. after this Mary Beth left the patient room and went to the adjacent room where the control computer was placed.



The operator, Mary Beth had worked for some time in the hospital and had quite a level of typing efficiency with her experience. But she failed to notice that the video monitor that would ideally give here the view to the patient room was unplugged and also the interlinking intercom was not in a functional state. However, since she had conducted this work before, she proceeded with the session.

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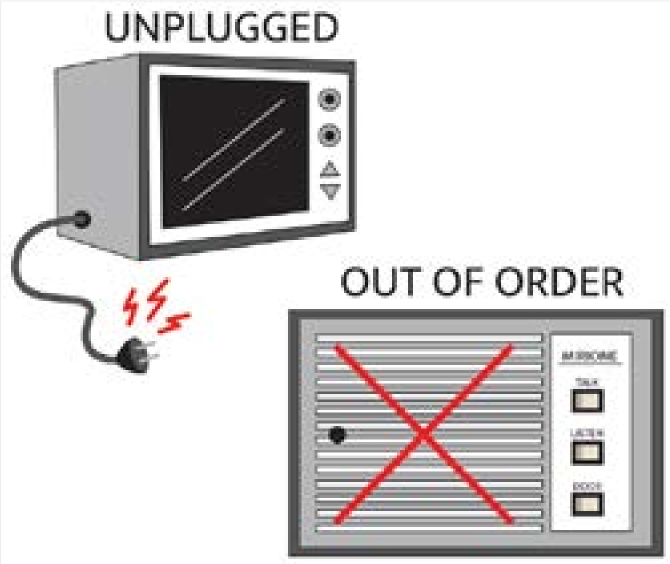
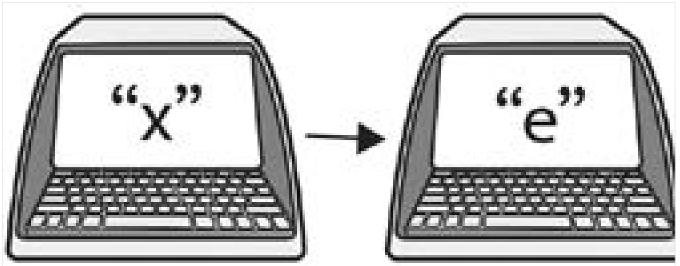


She entered the patients prescription data with great efficiency but then realised she had made a mistake in entering the wrong mode, x instead of e. That means that she had entered for the x-ray mode instead of the electron mode he was supposed to receive. She had been administering most x-ray treatments so was accustomed to the typing errors. It was an easy to fix mistake, just an up key that would edit the mode entry. After verifying all parameters and correcting the error within eight seconds she began the treatment process.



Inside the shielded patient room of the machine, Cox saw a flash of blue light and heard a sizzling sound before he felt a shot of heat on his shoulder.

A moment later the machine shut down displaying "Malfunction 54", and the treatment paused indicating a problem of low priority. The monitor showed no dose being fired, clicked in for a round two of the treatment. The sheet on the side of the machine showed the malfunction as a "dose input 2" error.

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In the room, Cox tried to roll to his side only to feel a second shot to his neck while he screamed to stop. He felt his chest muscles constricted, squeezing the air out of his lungs.

Mary Beth had no idea what the error code meant leading to her hitting the proceed a third time. Outside on the treatment table when he was shot a third time, he had better run out to get help.

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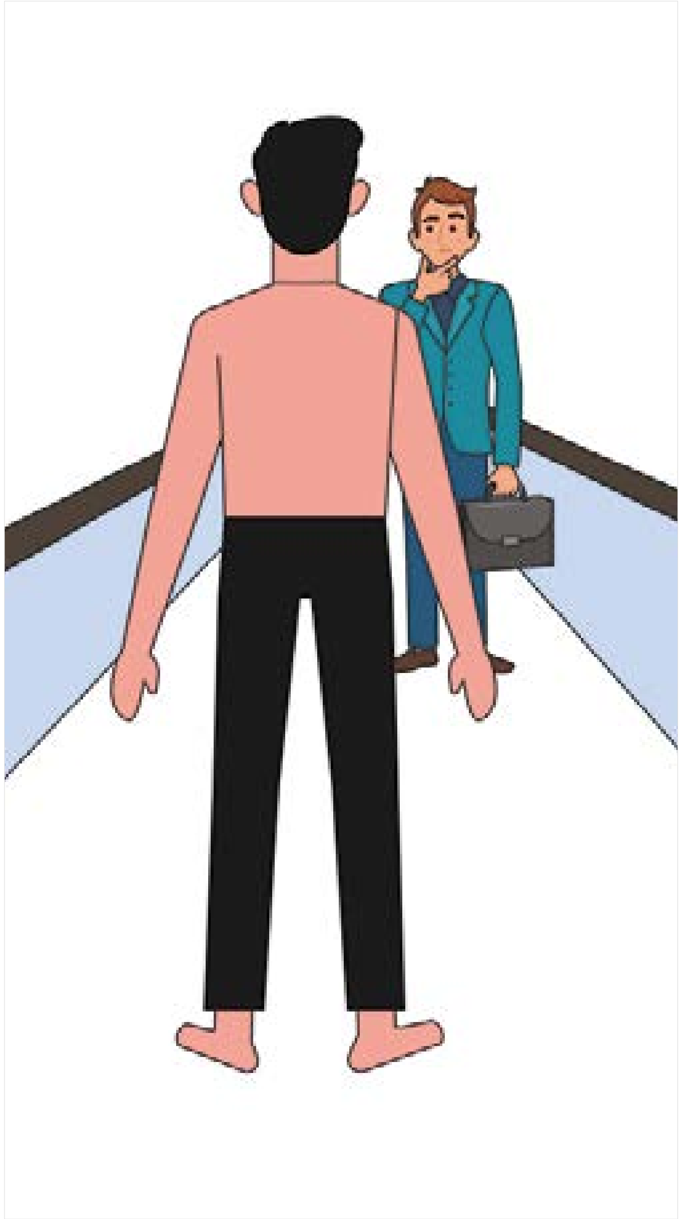
He ran out in fear of his life and writhing in pain, and bumped into technicians walking down the hall.



Eventually, Mary Beth realized that there was some problem in the treatment room, came out and was met with Cox at the Nurse's Station.

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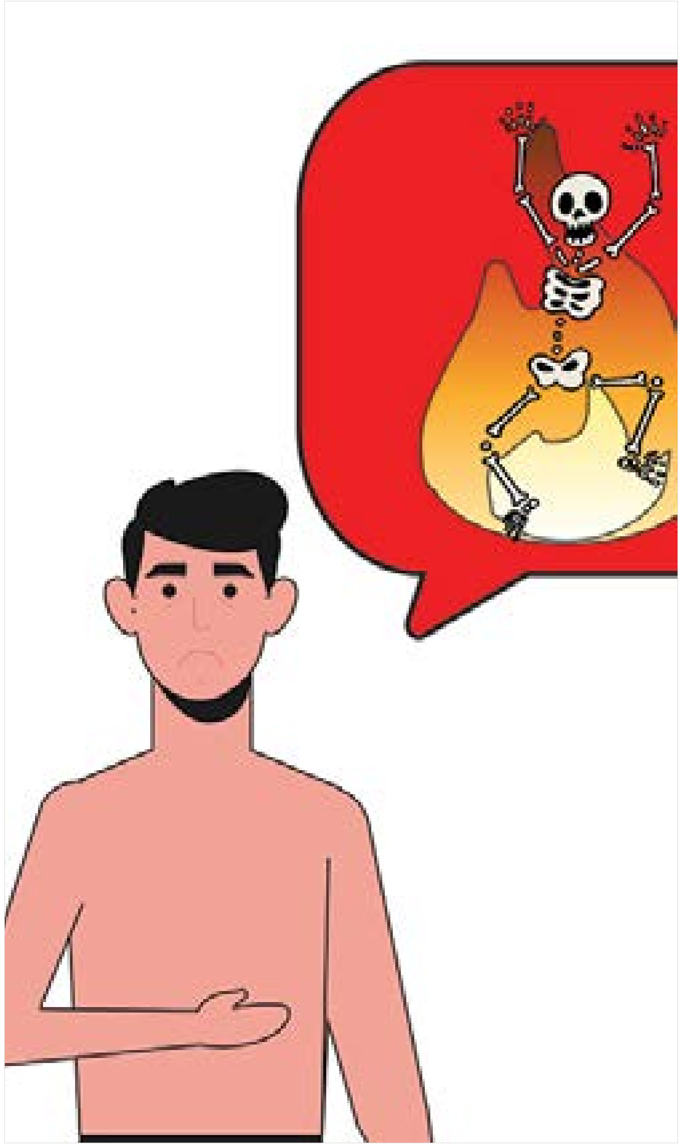
Cox went on to explain that he had received continued and painful shots of "electric shocks" while lying on the table.



Mary Beth responded by saying that nothing like that had ever occurred before and had no idea what might have caused it. The machine had malfunctioned and shut down automatically, showing that Ray had only received a tenth of his prescribed treatment!

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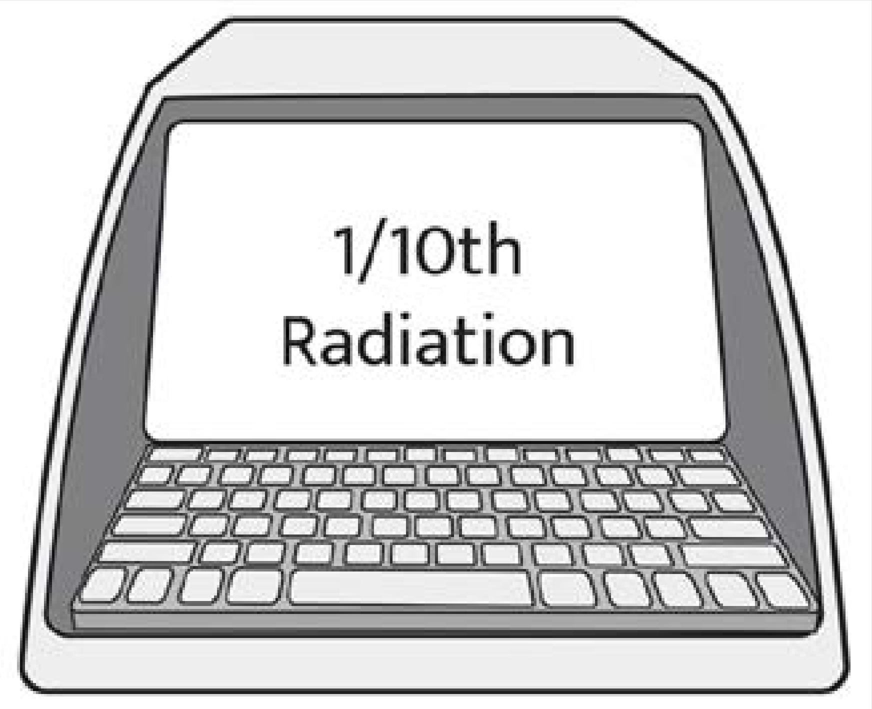

Not much information was made available in the instruction manuals or other documents explaining the malfunction. Later on one of the AECL technicians explained "dose input 2" as a dose that had either been delivered too high or too low. The monitor showed a substantial under-dose of radiation - about 6 monitor units was delivered while the operator requested 202 units.

The physician observed that Ray Cox had an intense erythema over the treated area but it suspected nothing more serious than an electric shock. He was discharged with an instruction to return if he suffered any further reactions. The physicist found the machine calibration with specifications with no problems, so more patients were treated throughout the day on the same machine.

In actuality, the patient, Ray Cox, had received a massive overdose of radiation concentrated to the center of the treated area, which was estimated a possible dose of 16,500 to 25,000 rads in less than 1 sec over an area of 1 cm. The patient experienced continued pain in his neck and shoulder area, later lost the function of his left arm and had periodic bouts of nausea and vomiting too. He was later hospitalised for radiation induced myelitis of the cervical cord causing paralysis to his left arm and both legs, left vocal cord and left diaphragm. He finally died of complications from the overdose five months later.

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The physicist and the operator spent a whole day of running tests on the machine but it did no help and he was not told of the other accident reports that had been made of overexposure. One of the engineers doing the investigation suggested that an electrical problem might have occurred.

An independent engineering firm conducting their own investigation, in their final report, explained that no electrical grounding problem was detected in the machine and was not capable of giving an electrical shock. The machine, having found no problem during the investigation was put back into service on April 7th, 1986.

e. East Texas Cancer Centre, April 1986: On April 11th, a male patient was scheduled to receive an electron treatment for skin cancer on the side of his face with a prescription was of 10MeV to an area of 7x10 cm. It was almost similar to the previous occurrence of radiation overdose in the same year. The patient died three weeks later of overdose on May 1st, 1986. He suffered disorientation which progressed to coma with a fever of 104 degrees Fahrenheit, and neurological damage. An autopsy showed acutely high dose of radiation injury to the right temporal lobe of the brain and brain stem.

f. Yakima Valley Memorial Hospital, 1987: On January 17th, the second patient of the day was scheduled to receive two film-verification exposures of 3 and 4 rads electron + 79 rads photon treatment. Later after the accident with Therac-25, AECL's preliminary measurement of the dose delivered on the day when the turntable was in the field-light position was estimated to be 4000 to 5000 rads. Since two attempts were made, it was estimated that the patient had received an approximate of 8000 to 10000 rads instead of the 86 rads he was supposed to receive.

Insights For Interface Design:
Therac-25 served as a major lesson for human factors and interface design of safety-critical systems. The insights gathered have been generalizable to almost every industry that employs safety-critical devices. We present some interrelated learnings that are applicable to interface design.

a) Need for proper requirements: Safety depends on the context or more specifically on the system it is used in and not on the software itself. In most if not all accidents involving the software resulted from flawed software requirements and not on its implementation. People misunderstand that software is safe, if it satisfies the requirement of the software. But most software-related accidents, oftentimes, do not involve coding or implementation errors but requirement flaws. In order to reduce software-related accidents, proper safety-critical requirements are important for building safety into these machines. Safety can't be ensured at the end; it has to be built in from the beginning. **Therefore, we need good requirements right from the very beginning including ones for the human interface.**

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b) Inadequate investigation of incidents or follow-up on accident reports: Most of the time of such technological accidents the blame is put on the operators rather than acknowledging the technical and interface design errors. Blaming on the operators, leads to patching the symptoms but does no help in understanding the systemic causes of the loss. Unfortunately, the blame game finds operators as their primary target. Changing operators results in fixes-that-fail. Thus, the accidents remains latent in the system regardless of the operator being changed. In these situations, in order to prevent future accidents, the role of the entire system needs to be addressed for understanding the accident. **Thus, proper interface design and associated issues resulting in accidents should be recognized as a systemic concept in safety-critical system. Further, they should be properly investigated with appropriate models and frameworks.**

c) Safe versus "friendly" user interface, role of "human error": In safety-critical systems, there is often a tension between safety and "ease of use". Oftentimes, the sine qua non of interfaces is to make them simple and easy to use. However, in case of safety, we should ensure that actions through the interface that may lead to unsafe states (hazards) are relatively difficult as well as have proper checks and balances. There should also be provision for the operator to recover from slips and mistakes through the interface by providing appropriate recovery mechanisms. This will ensure that operators are not blamed for flawed interface design. **In other words, we can design safety into the system. "Human error" in many cases maybe a misnomer.**

As the case-study demonstrates, our main challenge is to understand, how to design for the human in complex technological systems to which we turn next.

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Interface Design for Complex Technological Systems

In the last century, there was a growth of new technological sectors. These included rapid changes in areas such as nuclear, oil & gas, aviation, and chemicals, among others. All of these sectors involved not only the growth of the individual products but an interconnected systems of technologies along with people involved in the operation and maintenance of these integrated technologies. These systems are often complex in nature an involve a lot of uncertainty in their operation.

As these systems slowly developed, there was a rapid recognition that appropriate care has to be taken to ensure that these systems do not malfunction. Specifically, in safety-critical systems, malfunctions result in incidents, accidents, disasters and catastrophes. The hazards that these technologies, specifically nuclear and chemical, pose are not only limited to the limited to the immediate but lasts over subsequent generations. One can only think about places such as Chernobyl in erstwhile USSR or Bhopal in India where health implications of systemic disasters have been appalling. Therefore, a major challenge in these systems has been the need to ensure reliable operations. In order to ensure systemic operations, a crucial aspect of these technological systems has been the inclusion of the human as part of the overall system.

HMI design in technological systems has been studied extensively in cognitive systems engineering, a sub-discipline of Human Factors intersecting with Systems Engineering. For ease of understanding we will divide the involvement of the humans in technological systems in two categories. The first category deals with humans in-relation to other humans (groups, teams and organization, including health and occupational safety).

The second category deals with humans in relations with the immediate technologies — human machine interaction. This second category is the key idea that will be explored in this tutorial. Our main challenge is to design the human machine interface (HMI). It should be noted that the these complex technological sectors involve a heavy emphasis on the engineered dimension. This heavy technological focus imposes certain constraints on the activities of the users. In other words, the HMI design challenge is to design in such as manner so as to balance both the technology and the human together. This will ensure through the process of design that the operator is efficacious in any given situation while ensuring overall systems safety. Human factors researchers have, therefore, emphasized the harmony between the humans and technologies by ensuring a “joint-optimization” of the two.

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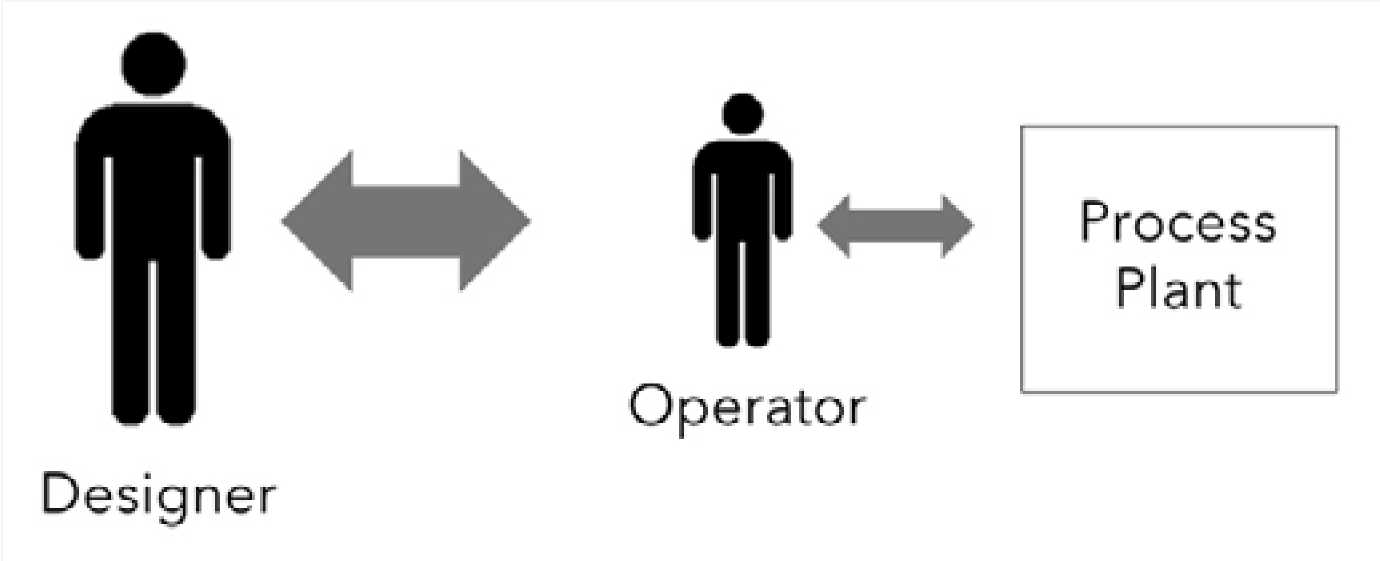
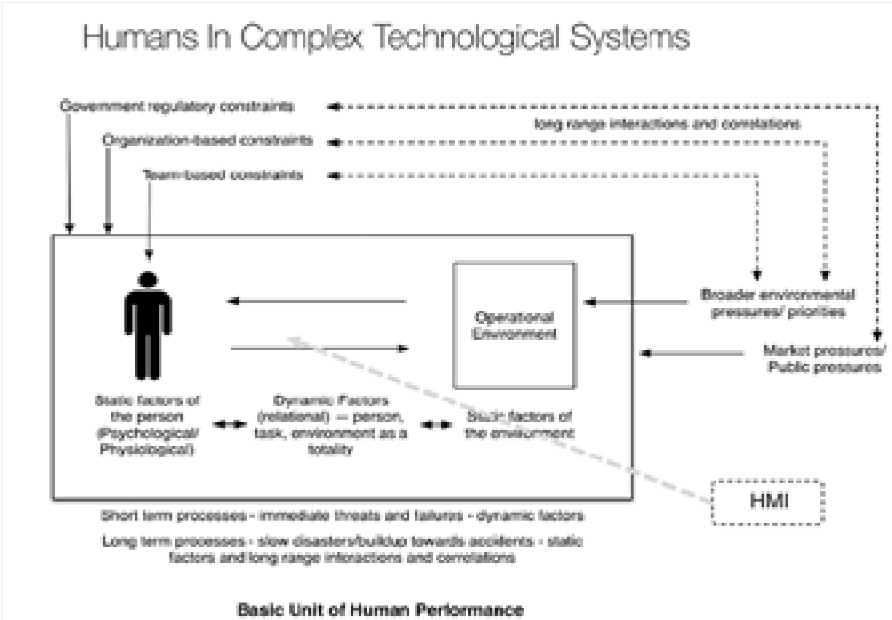


Human and technology taken together in a unified whole: "joint optimization" of humans and technologies.



Role of human technology interaction in complex technological systems. Adapted from Kyriakidis, Kant, Amir and Dang, 2018.

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In addition to the above, the design of HMI in technological systems should be human-centred; i.e. it should support the mental models of the operators involved in the operating the system while taking the technology into account. Towards this end, User-Centred Design (UCD), has been quite successful in promoting the need for involving the users right from the beginning of the planning and design process as well as throughout the systems life-cycle. While the need to ask users and get their feedback at all stages has been highly efficacious for design, there are certain limitations that UCD faces in highly complex technological systems.

First, focussing on "users" as a category is not enough to design the HMI. This is because users and operators are different roles that humans take up in complex systems (Kant, 2017). Operation of systems will require mental models and activities of operators because it is differentiated from what users do in terms of interaction with the system. In other words, operators and users have different goals and in our case mindsets in the manner in which they interact with the system and the design process should be such so as to cater to the needs and requirements of the operators. Second, the operator's mental models of the complex technologies need to be addressed more holistically such that both novice as well as expert operators are able to deal with unanticipated situations such as abnormal plant functioning. In moments of acute unanticipated disturbance, operators, being human, may not have all the vantage insights that need to be addressed for operation.

In order to deal with unanticipated situations as well as having a holistic understanding of mental models for novices and experts alike, we have to understand the underlying constraints of technology and represent it in ways that becomes efficacious for the operators. By identifying the constraints imposed by the technology, we will be able to identify human activities that fit in within those constraints without violating them. Stated in design terms, the technological basis has to be represented in terms of an experiential basis. In terms of HMI design, if we are able to represent the technological constraints in the HMI such that the operators are aware of it, then during abnormal conditions, they will be able to act such that the constraints are restored and the system returns back to its normal functioning.

Therefore, our design challenges involves developing better representations, preferably, simple forms to depict the inherent complexity of the work domain, so that the operator's mental models are supported. Based on a number of studies done in a variety of technological sectors, researchers from human factors have found this approach of representing constraints to be quite beneficial for HMI design. In the discipline of human factors, a number of conceptual and design theories, frameworks and methodologies have been developed. In this primer, we will focus on one approach called Ecological Interface Design (EID) that has been significantly successful in addressing the challenges of HMI design in complex technological systems.

Note: It should be noted that the exposition of EID in this primer is at a broader level and is presented in an overview format. A more detailed treatment of EID can be found in books listed in Bibliography and Further reading section. In addition, the insights presented here about EID should be taken together with other principles and strategies used by designers for developing interfaces.

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Design for Operator Experience using EID

Interface design in complex technological systems is a multi-disciplinary endeavour. In particular, the approach of EID derives from engineering design and psychology. The engineering design roots can be traced back to the researchers at Risø National laboratories in Denmark starting from the 1960s. The Risø laboratories were setup by the Nobel Laureate Niels Bohr for the peaceful use of nuclear energy. Currently, Risø Laboratories is a part of Technical University of Denmark and focuses on sustainable energy (DTU: https://www.dtu.dk/english/about/campuses/dtu-risoe-campus).

Since the 1960s, the electronic division of Risø was involved in ensuring technical reliability of electronic equipment related to nuclear research reactors. Over a period of time, the group started to recognize that ensuring technical reliability was not enough for the overall plant functioning. The human operator had to be taken together with the power plant to ensure overall plant functioning and reliability. In other words, the problem of technical reliability was reassessed as problem of human systems reliability. In the process of recognizing the role of the human, a necessary emphasis was placed on the design of displays. The key idea was that the human was system component and the technological system, the human's environment. This is one of the most fundamental insights for understanding interaction design in complex technological systems. In addition, over a period of a few decades, human operators and their activities were studied and a variety of other insights were formulated about operator performance (for example, use of skills, rules and knowledge taxonomy of human performance for proper interface design). These insights as well as others led to the creation of several conceptual structures that designers could use for HMI design for complex technological systems. One such conceptual structure was the Abstraction Hierarchy (AH). This AH can be used by designers to elicit design requirements and form the basis in the design process (discussed in detail in the next section).

In the wake of Three Mile Island Accident in 1979, researchers started to recognize that interface design was of crucial importance to support the operators' diagnosis of the mal-productive changes in the powerplant. Appropriate information through the interface and subsequent actions through the interface would enable them to bring back the power plant to a normal state of functioning. During the decade of 1980s and beyond, there was a growth in a "human-centred" outlook for technological design. Towards the end of 1980s and early 1990s, the ideas from the Risø group, specifically the ones put forward by Jens Rasmussen, were coalesced in a series of publications providing the basis of HMI foundation for EID (example: Rasmussen, 1986; Rasmussen, Pjetersen and Goodstein, 1994). This work was built upon Jens Rasmussen's existing work in the past decades at Risø.

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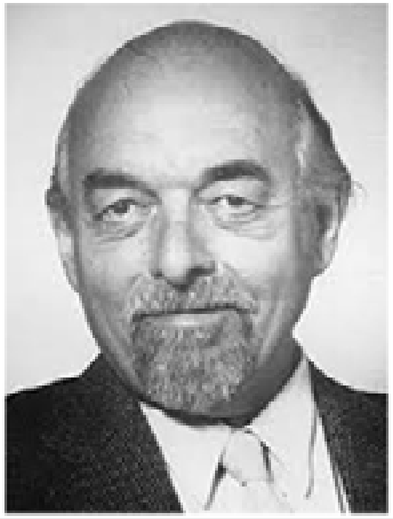

How to incorporate human behavior for overall systems reliability ?

Jens Rasmussen, 1926–2018

https://www.nae.edu/69218.aspx

Person as a systems component; Technological system as the person's context

http://www.dtu.dk/english/About/CAMPUSES/DTU-RISOE-Campus/Brief-history-of-Risoe

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Risø Laboratories, Denmark: 6 June 1958
Niels Bohr's vision of the peaceful use of nuclear energy
mid-1980s: Focus on sustainable energy

The EID approach was further developed by a number of researchers in the 1990s and beyond in areas such as HMI design for pasteurizers, petrochemicals, healthcare, military command and control, among many areas (Vicente, 2002;Vicente & Rasmussen, 1992). A more broader history of EID and Risø approach can be found in a number of articles and are provided in the Bibliography and Further Reading section. In the next section, we will take a step-by-step approach beginning from requirements gathering towards developing graphic forms for HMI.

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The Design Process

In the previous sections, we identified the challenges of interaction design in complex systems. Specifically, we noted the limitations of UCD for these systems as well as the need to understand the technology in experiential terms to support the mental models of operators. In this section, we will look into how we design interfaces for complex systems. Earlier, we had highlighted the need for a "joint optimization" of the human and technology. Therefore, one challenge is how to depict the constraints inherent in the technology so that the operators can act effectively on the system. HMI should ideally be designed in such a manner such that operators can act effectively on the system whenever required, in light of overall system safety. In order to achieve the design of an HMI, we will follow a few steps outlined below (we will only consider design in this tutorial and not evaluation, due to the intended scope). Further this section derives its steps from the following texts: Bennett & Flach (2011, 2013); Burns & Hajdukeiwicz (2004); Burns (2013). These texts are listed in the further reading section.

Step a - Understanding work domain, activity and processes
The first step of the HMI design process is to identify the boundaries of the problem under consideration. Identifying boundaries will help in understanding the nature of the system, tasks that operators will perform as well as have an eventual effect on the HMI design. Identifying the problem boundary is an iterative process. Once the designers start understanding the nature of the system and the work domain under consideration in more granular detail, they will be able to frame the problem boundaries for the particular system under consideration in a much more coherent manner. Typically, while framing the design problem, designers should not be including existing interfaces and interface elements at the outset. This is because the goal of the design/redesign is actually to introduce a new interface. Typically, we would want to include technological entities that the operator has to interact with (monitor, supervise or control) in order to do their work. Along with identifying the problem boundaries, a proper understanding of the operators's activities, background capabilities and limitations is required. This can be achieved by field studies and information gathering methods such as interviews, observations, critical incident analysis, study of error logs and work-shift records. Along with the operators, there is a need for an understanding of technology in experiential terms. We turn to this issue in the next step.

Step b - Identifying design requirements and associated constraints
Once the insights and data are acquired in Step 1, we will use Step 2 to identify the design requirements. this step is covered by qualitatively modelling the requirements using an analysis framework called Cognitive Work Analysis (CWA). The CWA consists of five steps. the first step called the Abstraction Hierarchy (AH) is used here to elicit design requirements. The AH, and the corresponding CWA, are a part of a broader framework that has been developed by Rasmussen and colleagues (Rasmussen, 1986; Rasmussen, Pjetersen and Goodstein, 1994). The framework addresses various dimensions ranging from the work domain activities and operators.

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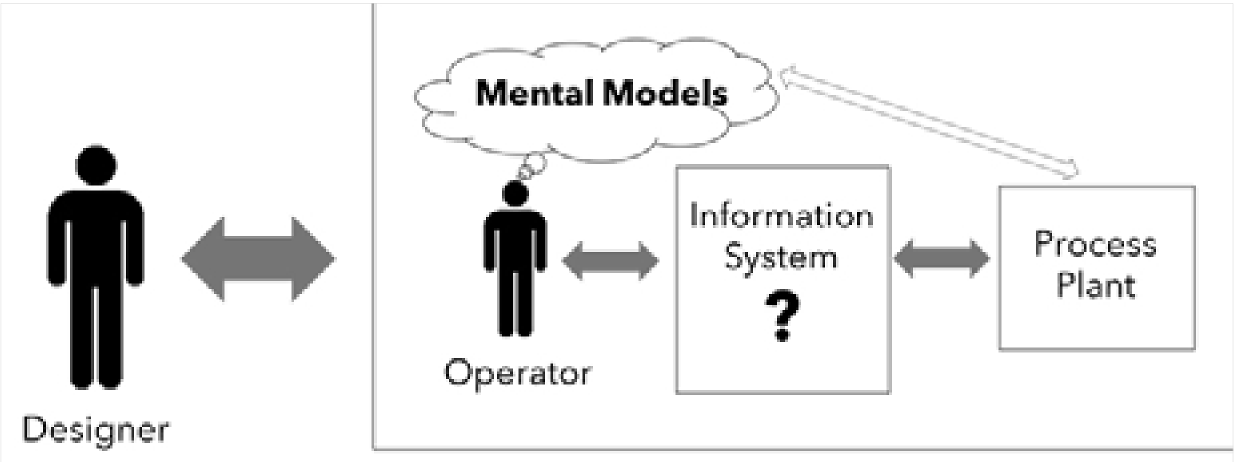
In this tutorial, we are focussing on the AH which represents the work domain in experiential terms for developing the interface. Other steps are developed in greater detail by researchers such as Kim Vicente (1999) and will not be developed here in greater detail. We will be focussing on the first step that models the work domain under consideration. The modelling for eliciting out requirements for interface design can be achieved by this tool AH which is used for modelling the work domain qualitatively.

The AH was developed to understand the work domain or the technical environment that served as the basis of human decision making for operators. The AH has its roots in everyday practice in high-risk systems for understanding the mental models required by operators and maintainers in trouble-shooting technological equipment. Based on a few decades of research, Rasmussen identified a few generic categories of mental representations that operators use in understanding technological equipment. These categories were grouped together to form the AH. They range from functional purpose from one end to physical form at the other. These mental representations had a basis in the physical and technological dimension or the operator about the system. Therefore, it served as a basis of a combined mental model of the system. In this subsection, we will develop the AH in further detail to show how we extract information requirements for design.



How do we support mental models of the operators and use it for the design of technology using a structured design process.

In the AH, the figure shows a number of categories that are arranged in an ordered set. These categories can be understood as corresponding to different mental representations of the system that a person may use to understand the functioning of the system. These categories of representation connect the technical dimension of the system to the experiential basis of the operator. In order to demonstrate the various categories, we will use the example of an ink jet printer. Its complicated make-up will serve as an example to help us in understanding of the AH.

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The first category involves functional purpose. In this level, the main issue is to capture the overall objectives of the system. The key ideas that are pertinent to this category are to capture generic descriptions that hold over the entire work domain under consideration. For example, the overall functional purpose of a printer is to print copies faster, use less ink and save money.

The second level labelled as abstract function addresses basic principles , law-based understanding and relationships that exist throughout the system. At this level, the focus of understanding is in terms of abstract principles. For example, in the case of the printer, we will think about stoichiometric relations when we calculate how much black ink is required to print 500 words on an A4 size sheet of paper. Therefore, the level of abstract functions allows for representing one category of mental models that the operators may employ while trouble-shooting.

The third level of generalized function represents the process involved in the technical functioning of the system. Oftentimes, in the process control systems, operators try to focus on the processes to gain an understanding of how the system is functioning. For example, in the printer, there are multiple physical processes relating to the paper moving through the printer as well as chemical processes related to the ink transfer on paper.

At the fourth level, of physical functions, the various components, objects and sub-assemblies are presented along with their capabilities. At this level, the representation is at the level that tends towards physical substructures and their associated functions. In our printer example, we will be considering components such as printer body, rollers, motors, among other entities and their associated functions.

Finally, at the level of physical form, we take into account the physical dimensions and attributes of the work domain or system under consideration. These include size, shape, color, appearance, location or general conditions of the various entities. In the printer example, we include many such attributes, such as dimensions of the ink bottles, paper thickness as well as other dimensions required for the representing the physical form dimensions of the work domain.

In the AH, these five categories are presented together as a unified structure. The upper layers tell us about the "reasons" of correct functioning of the work domain; whereas, the lower layers tell us about how possible malfunctions can propagate upwards and throughout the system. Along with the structuring of the hierarchy, the various levels are also connected to the levels above and below each other through links that are knows as means ends links. These links give us an insight into how the various categories or levels are interconnected to each other. If we focus on any one level, we answer the question "What?". If we focus on the level above, we get an answer to the question "Why?" and when we focus on the level below, we get an answer to the question "how?". This linkages of the "why-what-how" questions allows designers in structuring information and deciding on the priorities in the actual interface. This is discussed a bit later in this section. Up till now, we have described the abstraction hierarchy and its ability to represent a technological system in experiential terms derived from categories of operators' cognitive activity and decision making in a variety of situations.

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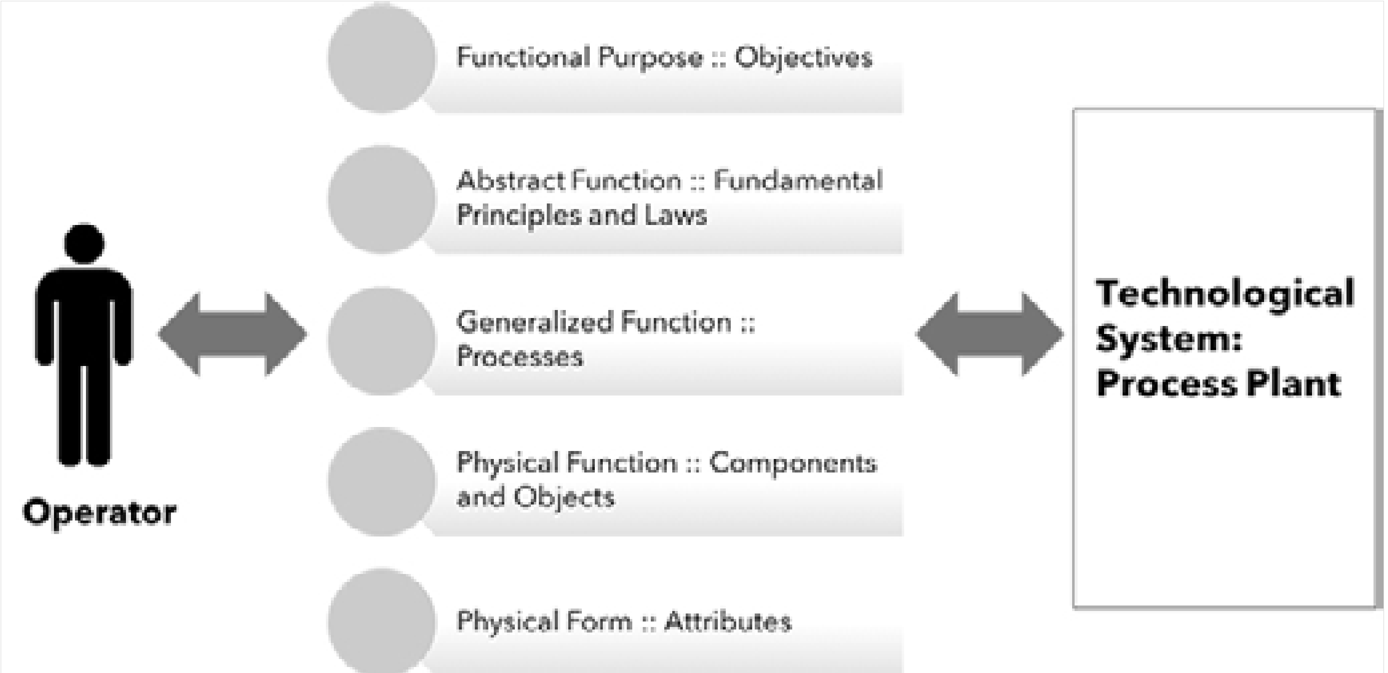
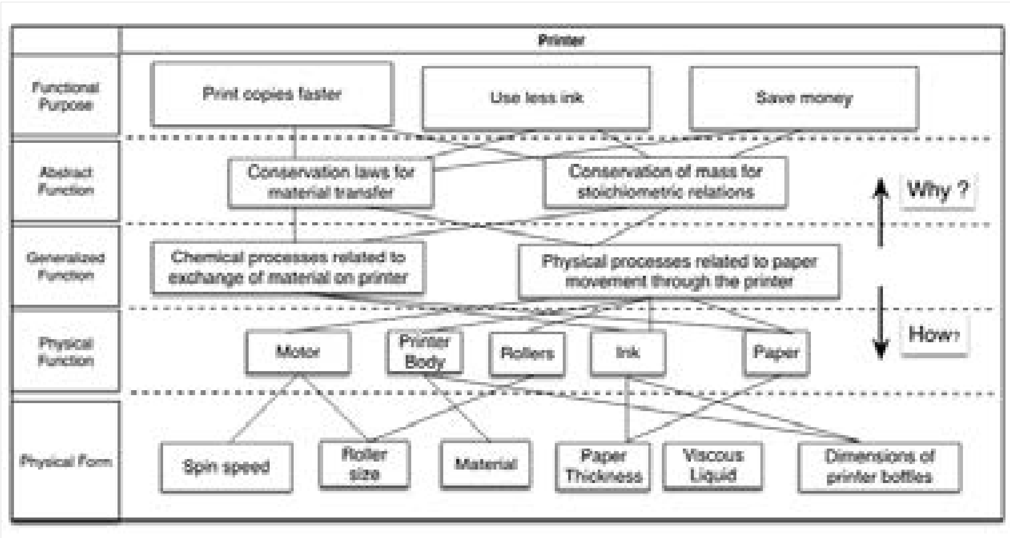


Levels of the abstraction hierarchy derived from a study of mental models.



Abstraction Hierarchy of a printer. Notice the why?-what?-how? links.

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Based on these categories, we will derive a list of information requirements. These information requirements tell us about the various aspects we need to consider in our design and are derived in the process of filling up the abstraction hierarchy. The AH help us to derive these requirements in the form of variables that we put in at various levels of abstraction placed in the categories. From the abstraction hierarchy, these can be listed in terms of various categories to help the designer identify various requirements (see Figure below). These requirements will then be used in conjunction to develop graphic forms with the identified constraints and the means ends links in terms of the assigned priorities in the subsequent steps.

Functional Purpose	Speed of delivery
	Cost (decrease money)
	Reduce material (save ink)
Abstract Function	Conservation of mass
	Conservation equations for ink transfer
....	....
Physical Form	Spin Speed
	Roller Size
	......

List of information requirements

Along with the information variable, the next step that will help in the design of interfaces is the identification of the constraints of the system as reflected through the variables. In order to extract constraints, we ask questions about the limits and possible interconnections. For example, in the case of the printer, we may ask at the level of the functional purpose: How many copies? How quickly? We ask similar questions of the other levels. E.g.
• Generalized function: maximum and minimum roller speed?
• Physical Form: size of rollers?, etc.

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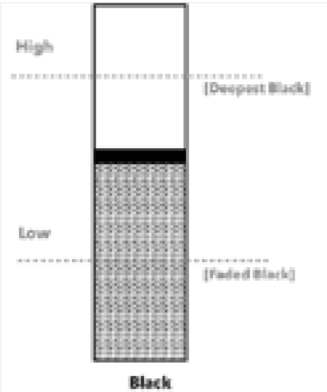
Identifying the constraints at various levels of the AH provides us with very specific insights about what is permissible for individual variables as well as at the level of multiple variables. These constraints along with the identified information variable serves as the basis of graphic forms and interface elements.

Step c - Identifying or developing graphic forms for displays

After the information requirements are addressed, our next step is to address the graphical forms of displays. Currently, this issue has been addressed by a number of very good design books that that include generic principles of information design and interface design elements. These generic design principles should be used judiciously with the principles of EID. Therefore, they will not be addressed here in greater detail and our focus will be on EID, in order to show how graphic forms could be developed to demonstrate the underlying constraints of the technological system that the operator can understand.

When we want to develop a new graphic form based on the information requirements, we ask questions such as the following: whether we need to depict one variable or a multitude of such variables? How are the variables related? How will the operator view and understand these variables in context? Are there existing graphic forms that the operators rely upon to make sense of their work?

In our design, we have to balance both the single variable constraints and the multi-variable constraints and depict them in the interface. For example, single variable constraints could be ink in one bottle. In this figure below, we are adding information that enriches the basic variables to demonstrate what can be achieved by manipulation of the variables. In other words, we are depicting the affordances of the variables that can be manipulated by the operator. In the figure, we have added a high cut-off for the deeper black color to be achieved; i.e., it shows that beyond this color, the color will be completely solid; whereas, below the lowest cut-off point the colour will be presented as faded. The two lines in the middle depict the current level of the ink in the cartridge.



Graphic forms showing single-variate constraints on activity (points beyond which deepest to faded black is represented.

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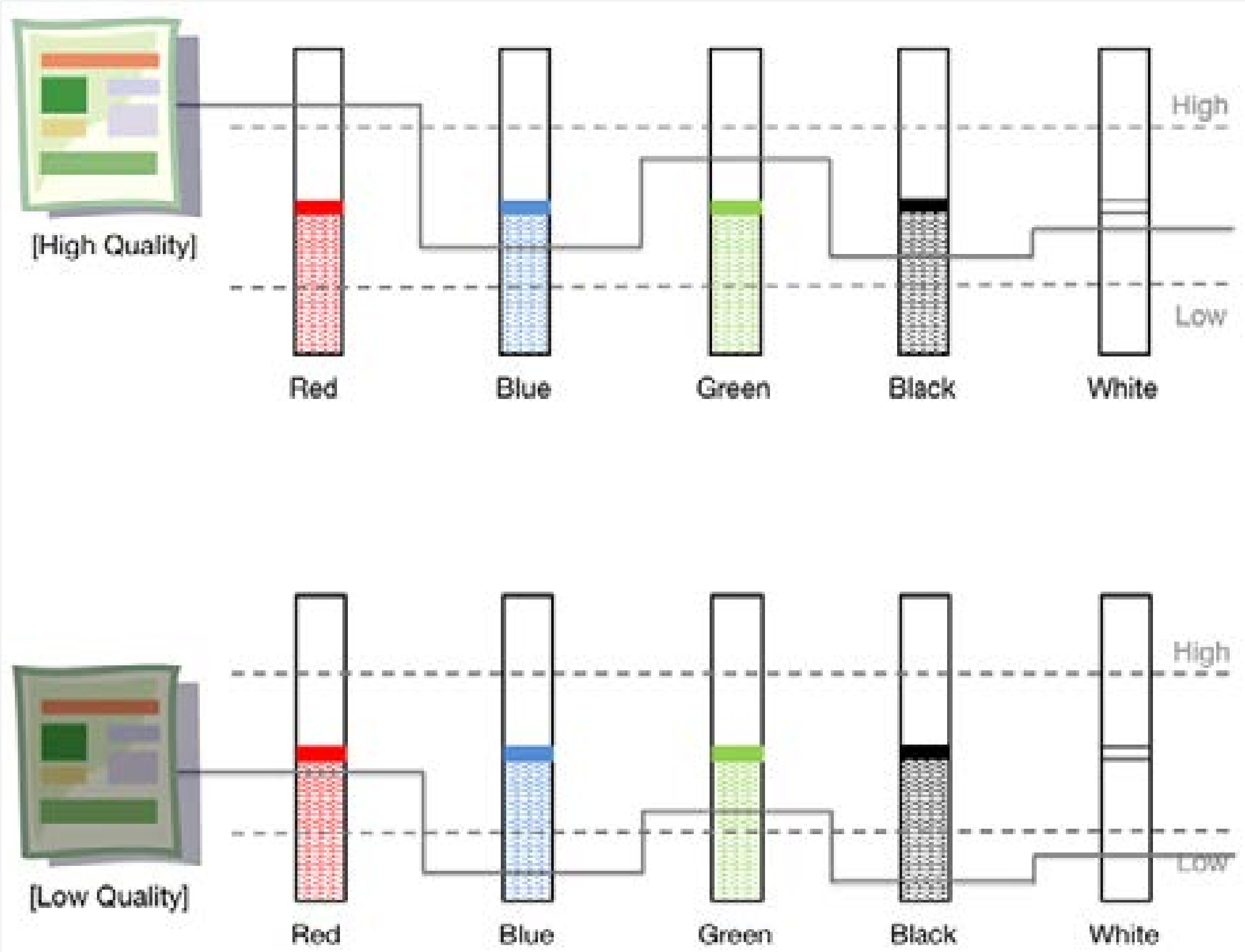

Two graphic forms showing multi-variate constraints on activity of printing. the high quality (high quality preset) can be accommodated with a certain level of inks present; whereas, if the requisite amount of ink is not present then a lesser quality of print (low quality preset) could be obtained in the existing ink.

Along with single variable constraint, let us now consider a multi-variate constraint. For example, if you were printing a picture with different colors and your ink was limited. Then, the interface should ideally, help you to identify the current state as well as opportunities for further action. The figure of multi-variables show that given the amount of ink for blues and green, it is clear that a high quality print-out cannot be achieved. However, a low quality print-out is possible. Thus, multiple variables can be involved in depicting a constraint of the system to provide proper information.

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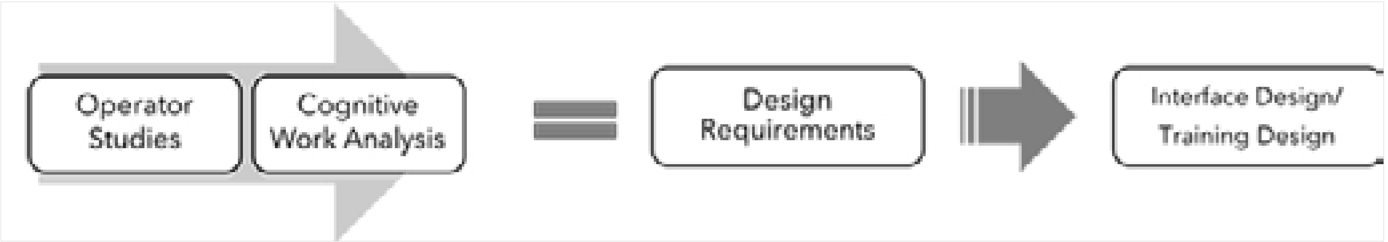
Step d - Assigning priorities and structuring the display
In our final step, we establish clarity in the interface by structuring the various graphic forms. This structuring is helpful in providing the operator coherence and meaning. Designers' use a number of principles (e.g. gestalt principles) to structure the interface elements and is often discussed in courses relating to 2D form and principles of information design. We will not go into those principles as they have been detailed in a number of design books and publications.

Based on the scope of our advanced primer, here we will discuss a crucial contributor from the AH — means ends links. Earlier, we had discussed the means ends (why-what-how) links that gave a generic insight into the structuring of the AH. One manner in which means-ends links work is by ensuring salience. Since operators may wish to see the functional purpose at the highest levels and may not move to the lower levels, we could improve the salience of the graphic. For example, one information variable can be made more salient as compared to others to depict its position in the AH; i.e., the broader levels of the aim of the work domain is addressed at the level of functional purpose and should be depicted at a more global level or maybe at the top corner of the interface to make it more salient.

Another strategy of improving design through the use of the means-ends links is to show the interconnections between variables that give information to the operator at any given point about "why-what-how" of the system's functioning through the interface. The individual graphic forms must be interconnected to each other in such a manner that it should be clear for the operator that the variables of the level of physical function are connected to the processes in the level of generalized function. The key idea at this stage is to depict various interface elements in such a manner that it provides coherence and clarity to the operator to support their reasoning during normal as well as abnormal functioning.



EID starting from operator studies in context to interface design

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Design Course

Human Machine Interaction Design

Introduction to Operator Interface/Experience (OI/OX)
by
Vivek Kant
IDC, IIT Bombay

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