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A Systematic Tool for Deriving Crew Console Layouts

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This paper describes the use of the Function Allocation Matrix Tool (FAMT) for designing spacecraft cockpit layouts. NASA's Constellation Program intends to return humans to the moon by 2020, followed by exploration to Mars and beyond. The Orion Crew Exploration Vehicle (CEV) will serve as primary vehicle for transporting the crew. Orion will be equipped with a modern 'glass cockpit' that will allow the operators to command and control all of the vehicle's systems via graphics-based displays not unlike those now common in modern flight decks. The design of Orion's displays and controls places an increased emphasis on human-computer interaction and usability. In particular, the use of the FAMT drove the process of allocating displays and controls to reach and visual zones within the CEV 604 configuration cockpit. The result was the baseline display and control configuration for the Orion spacecraft.

INTRODUCTION

NASA's Constellation Program intends to return humans to the moon by 2020, followed by exploration to Mars and beyond. The Orion Crew Exploration Vehicle (CEV) will serve as primary vehicle for transporting the crew. It will be capable of carrying crew to the International Space Station (ISS) once the Space Shuttle is retired in 2010, rendezvous with a lunar lander module, carry crews to the moon and beyond, and serve as the Earth re-entry vehicle (NASA, 2008). Orion is a capsule-type vehicle similar to, but significantly larger than Apollo. Orion will carry six astronauts during low earth orbit missions, such as those to the ISS, and four astronauts on lunar missions.

Orion will be equipped with a modern 'glass cockpit' that will allow the operators to command and control all of the vehicle's systems from one of two operator stations. Unlike the Shuttle flight deck, Orion will only have a small fraction of the buttons, switches and dials. Instead, Orion's operators will monitor and command the vehicles systems via graphics-based displays not unlike those of modern flight decks. As this would imply, the design of Orion's displays and controls places an increased emphasis on human-computer interaction and usability. The importance of human factors is reflected in the fact that NASA, for the first time, has mandated usability and workload criteria within the vehicle design requirements. As a result, human factors engineers are heavily involved in every aspect of Orion displays and controls design.

This paper demonstrates the use of the Function Allocation Matrix Tool (FAMT) for designing spacecraft cockpit layouts. In particular, it describes a method for allocating displays and controls to reach and visual zones within the baseline configuration for the Orion spacecraft.

PRACTICE INNOVATION

The FAMT and related human-centered design processes address how to systematically assign display and control functionality throughout a cockpit. While the FAMT was originally designed for investigating incremental additions of display or control functionality to an existing cockpit, it can be applied as with CEV to a completely new cockpit design.

Human-centered Design Process

The iterative human-centered design process for determining CEV crew console layout requirements is illustrated in Figure 1.

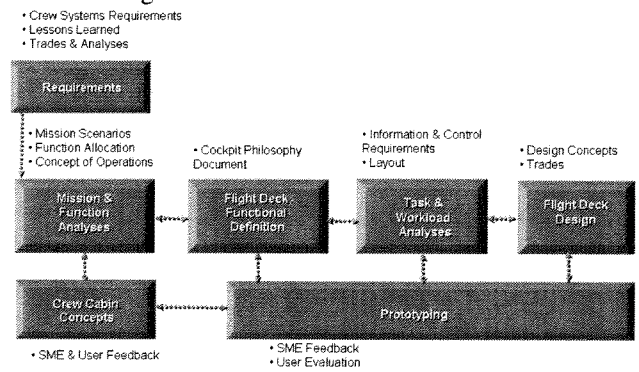

Figure 1. Crew Console Layout Methodology.

Mission and Function Analyses. The CEV Mission Operations Working Group defined a relevant set of mission scenarios and critical mission elements, so that all teams were using common terminology. These were then used to define initial operational requirements that started at a general (qualitative) level and progressed to a more specific level.

Derive functions (Function List). The displays and controls layout design process began by deriving the CEV function list. The primary source of function data was the CEV Concept of Operations document. Further functions were uncovered by examining Space Shuttle (current technology and procedures) and Apollo (similarity to interplanetary mission and vehicle type) records to determine the set of functions that have traditionally been needed for accomplishing similar mission sequences (e.g., launch, entry into orbit, docking, undocking, de-orbit, landing). The original list of functions is a living document that is updated as new information is gathered.

Functional Flow Block Diagrams. Block diagrams were developed for each mission phase. Initial concentration was on International Space Station (ISS) missions. The diagrams served two main purposes: matching functions to a timeline, and establishing parallel and sequential activities. Time

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tagging provided input to decisions on accessing displays and controls for task completion. Parallel activities indicate a need for simultaneous displays and non-shared controls. Figure 2 shows a portion of one flowchart.

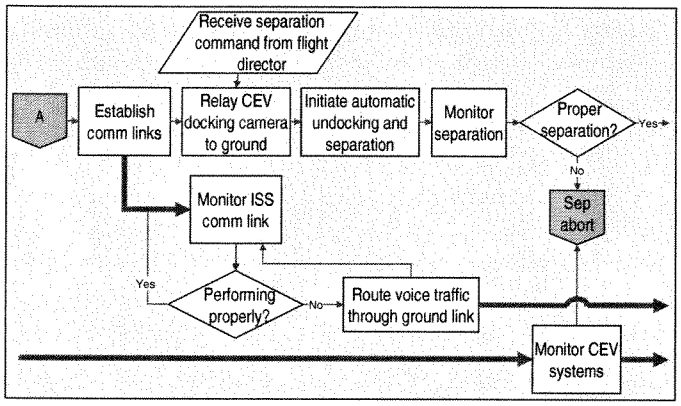

Figure 2. Functional Flow Block Diagram Sample

Each block in the diagram represents a higher level function. Each function may be comprised of several sub-functions and specific tasks. Since there are no detailed designs available for task identification, analysis occurs primarily at the function level. The thin lines in the flowcharts indicate sequential tasks. Parallel lines of blocks indicate concurrent activities. In some cases, blocks are connected by thick lines. These indicate that the task is continuous over the duration represented by the line. Where available, timelines are displayed on the bottom of the flowchart.

FAMT Application

Control/Display identification. The first step in applying the FAMT is to examine a function and to classify it as one or more of several basic task types: control of flight, navigation, communication, systems management, other. The first four are analogous to those used in the aviation domain. The "other" category captures those tasks which are not directly related to CEV function but require use of astronaut time and resources (taking photographs, stowing equipment, etc.) or that are more cognitive in nature (decision making, crew resource management, etc.).The second step is to indicate whether the function requires displays, controls, or both for the crew to complete the associated tasks.

Functional rankings. The ratings part of the FAMT (see Figure 3) makes use of experts from systems engineering, human factors, and subject matter experts to rank each function in four categories: hazard criticality, direct control of spacecraft, operational criticality, and frequency of use. Since CEV is in the early phases of design and it is impossible to obtain experimentally derived data, preliminary judgments are made based upon the function classification and the rater's experience. For each category a ranking of 1 to 5 (low to high correlation with that function) is given.

Mission Derived Function	CTRL FLIGHT	NAV	COMM	SYS MNG	OTHER	Control	Display	Alert	Hazard Criticality - 1 low - 5 high	Direct Control of S/C - 1 low - 5 high	Operational Criticality - 1 low - 5 high	Freq of Use, (F) - 1 low - 5 high	M+C+F
Deorbit													
Monitor deorbit burn		x		x			x		5	1	5	5	16
manually control deorbit burn	x	x		x		x	x		5	5	5	3	18
monitor CM separation from SM				x			x		5	1	5	1	12
manually trigger SM separation				x		x	x		5	4	5	1	15
Monitor SM separation burn		x		x			x		5	1	5	1	12
read and call out procedures				x		x	x		5	1	5	4	15
manually control SM separation burn	x	x		x		x	x		5	4	5	1	15
monitor trajectory		x					x		5	1	5	5	16
monitor CEV systems				x			x		4	1	4	5	14
monitor comms				x			x		2	1	4	5	12
abort	x	x		x		x	x		5	5	5	1	16

Figure 3. FAMT Sample with functional ratings.

- Hazard Criticality: Is this function critical to the safety of the crew and spacecraft? A ranking of "1" would indicate that the function has little to do with safe operation and assured crew return. A ranking of "5" would indicate that access to displayed information or the ability to make control inputs would affect crew survival.
- Direct Control of Spacecraft: How does the function directly affect the motion of the spacecraft? Adjusting the cabin temperature ranks very low, but adjusting the vehicle closing rate with the ISS ranks very high.
- Operational Criticality: Functions are ranked according to how they impact mission success. This must be differentiated from hazard criticality. Inability to adjust cabin temperature may mean that the crew is forced to wear suits for the duration of the mission. This would drastically affect the capabilities of the crew and may cause an early return.
- Frequency of Use: When estimating, it is important to remember the mission phase and nature of the activity. Manually orienting the CEV for de-orbit burn may be a very infrequent activity, but when undertaken, will consume the astronaut's attention completely.

Display area allocation. After the independent FAMTs were completed team members worked together to reconcile all differences in the individual scorings to create an overall team score. The team significance score was then used, following FAMT protocol, to rank the various information and control needs and thus where each should be placed relative to the resting line-of-sight in a microgravity environment following standard human factors engineering protocol.

A high significance score indicates a function with very high potential workload. Displays and controls should be placed for maximum ease of use. A low score indicates that placement in a less accessible area may be acceptable (see Figure 4 and Table 1).

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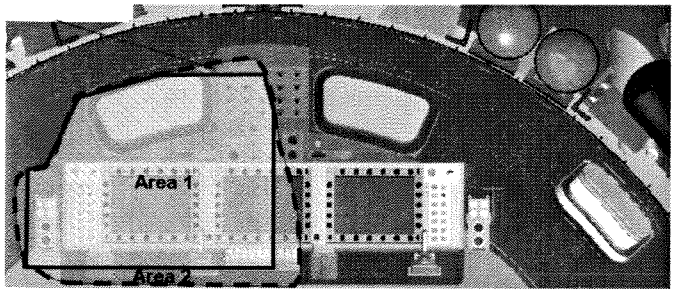

Figure 4. Access areas defined by HSIR minimum female reach (dotted line).

Table 1. Display and control requirements for each Area.

Required Access Level	Display Access Requirements	Control Access Requirements
Area 1, scores = 16-20: defined by commander's and pilot's primary eye rotation range and reach envelope.	No head motion required.	Little arm motion is required.
Area 2, scores = 11-15: represents display/control area shared between the commander and the pilot.	Field of view may require head motion.	May require substantial arm motion.
Area 3 (anything not within Area 1 or 2), for scores <= 10: represents areas that are at the edges of the field of view and reach envelope.	May be towards limits of field of view with head movement.	May require substantial arm and body motion.

For the CEV 604 configuration, we divided the workspace into three groupings based on anticipated access levels required by crew members. In all cases, it was important to remember that these rankings suggest the minimum acceptable locations. A display or control can always be placed in a higher ranked area if there is sufficient room. In Figure 5, a display or control was ranked a "1" ("primary") if it was in Area 1, and a "2" ("secondary") if it was in Areas 2 or 3.

Description		Access Level												
Mission Derived Function	M-C-F	Display Access	Control Access	Commander's Primary Display	Commander's Primary Controls	Comander's window	Pilot's Primary Display	Pilot's Primary Controls	Pilot's Window	Shared Display	Shared Controls	Overhead panel	Other Window
Deorbit													
Monitor deorbit burn	16	1		x			x			x			
manually control deorbit burn	18	1	1	x	x		x	x		x			
monitor CM separation from SM	12	2								x			
manually trigger SM separation	15	2	2							x	x		
Monitor SM separation burn	12	2								x			
read and call out procedures	15	2	2							x	x		
manually control SM separation burn	15	2	2							x	x		
monitor trajectory	16	1		x			x			x			
monitor CEV systems	14	2								x			
monitor comms	12	2								x			
abort	16	1	1	x	x		x	x		x			

Figure 5. FAMT sample with access level.

Workspace Zone Definition

The workspace zones were generated by modeling the fields of view and reach envelopes of the expected astronaut population.

Field of View. Figure 6 shows the different fields of view (FOV) as they apply to a side by side workstation with three horizontally arranged displays. Ergonomic computer mannequins of a minimum size female and a maximum size male were placed in a computer-aided design (CAD) model of the CEV, using dimensions from the Human Systems Integration Requirements (HSIR) (NASA, 2006). Each was positioned according to current seat designs, restraints, and pressure suit volumes. Displays and crew windows were arranged in the CAD model according to field of view guidelines (NASA, 2005). See Table 1 for display area definitions.

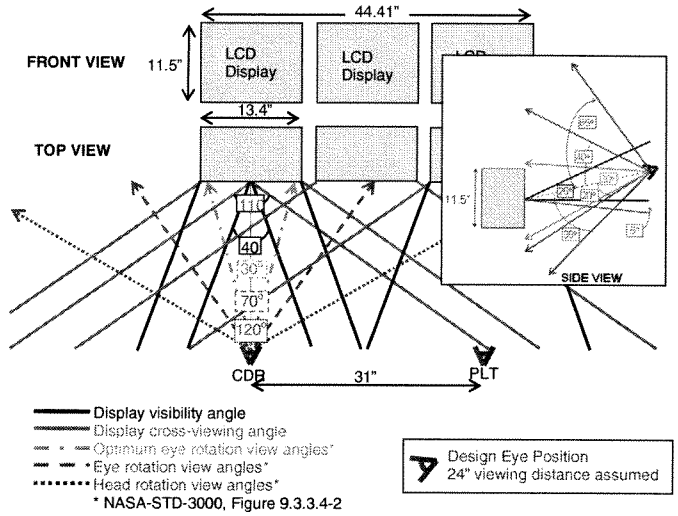

Figure 6. Screen viewing angles: top, side, front.

Reach Envelopes. Reach envelopes were also determined using the ergonomic computer mannequins. Figure 7 shows the CEV 604 configuration thumb tip reach envelopes of the HSIR minimum female and maximum male body sizes. See Table 1 for reach area definitions.

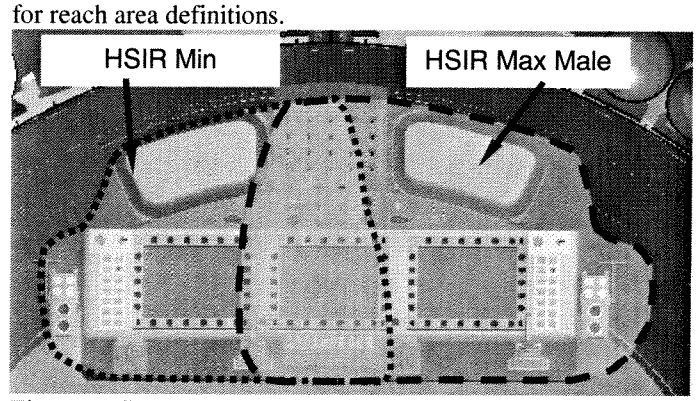

Figure 7. Seated Thumb Tip Reach Envelope

FINDINGS

The resulting CEV 604 configuration crew console layout is based on the control and display access requirements obtained from the FAMT

Crew Console Layout

Figure 8 illustrates the final CEV 604 configuration layout (future updates will be done on subsequent configurations to use the most recent spacecraft dimensions).

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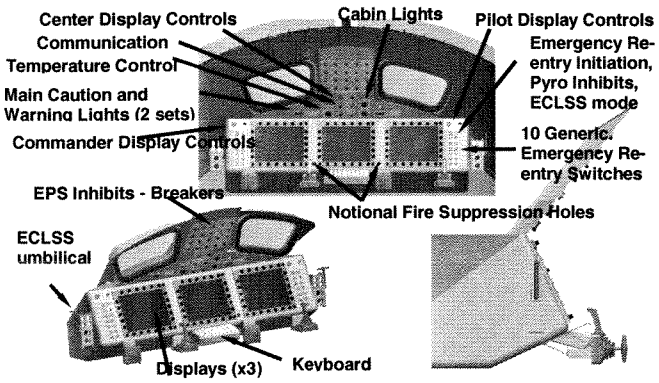

Figure 8. CEV 604 Configuration Crew Console Layout.

Control Spacing and Sizing. Control spacing, control sizing, and appropriate device requirements were derived from applicable documents (e.g., Department of Defense, 1999; NASA, 2005). When spacing devices, we generally did not use minimum spacing requirements. Specific guidance for gloved use was not always available and we wanted to ensure the ability to operate all controls when wearing gloves. We also assumed all control devices would be protected against inadvertent activation, e.g., toggle switches are protected by barrier guards, and lever lock switches are used wherever inadvertent action would be detrimental to flight operations or could damage equipment. Cover guards are used on switches where inadvertent actuation would be irreversible.

Hard Mounted versus Software Control. Our approach was strongly biased towards use of soft keys, accessible via either edge keys or a cursor control device (CCD) to select functions on computer displays, as opposed to having dedicated controls for each function. We generally only used dedicated controls for functions which we considered critical (high significance score) based on FAMT, and for which we believed an immediate response would be required (like for manual fire suppression). The goal was to avoid having crewmembers delay in accessing needed functionality in an emergency situation. One exception to this rule was dedicated rotational and translational hand controllers, due to expected crewmember experience, transfer of training, and initial subject matter expert feedback. We also provided dedicated temperature and cabin lighting controls as a convenience due to anticipated frequent use.

Advantages to minimizing the number of dedicated controls include simpler wiring, which makes it simpler to do layout reconfiguration. This provides mission flexibility advantages. In addition, fewer controls save on cost (including certification cost), weight, and space requirements. There are also maintainability and upgradeability advantages with fewer hardware devices to service. Due to the limited number of control devices, the layout allows all crew console controls to be reachable by crewmembers even when seated.

Shared Controls. Shared controls were used wherever possible for the pilot and commander. This saves space and weight, while also supporting the customer goal of allowing operating crewmembers to view and confirm each other's operations. The reach analysis has shown that the shared controls are accessible to a HSIR minimum body size female commander or pilot (Figure 9). As such, the layout only duplicates controls (at both the commander and pilot workstations) that do not fit in the shared space or that might have immediate access requirements. An example of duplication is with the emergency re-entry pyro event controls (e.g., parachute deploy, hatch jettison).

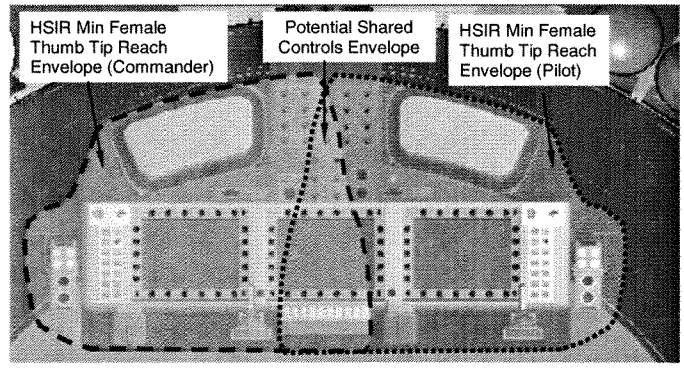

Figure 9. Potential Shared Controls Envelope.

Caution and Warning Indicators. The implementation of the caution and warning indicators for the CEV 604 configuration was based on a framework that has been tested extensively on aircraft flight decks (Dorneich et al., 2001). In a situation where there is an emergency or warning off-nominal situation, red caution and warning indicator lights activate, along with a corresponding aural annunciation. Details of the emergency or warning message would be available on an astronaut's primary display and the corresponding procedure would be available on the shared display. While the primary and shared displays would have the needed information, we decided to provide dedicated lights in the crewmembers' primary field of view to provide additional highly-salient visual alerts needed in emergency situations (e.g., fire suppression requirement from the HSIR). Placement of indicator lights, corresponding display formats, and controls is determined from FAMT access requirements.

Hand Controllers. Based on a trade study (Lockheed Martin, 2006) which included feedback from several subject matter experts, rotational and translational hand controllers were included to meet the System Requirements Document (SRD) requirements for manual control (e.g., rendezvous, docking, and proximity operations manual control requirement). The hand controllers for this configuration are similar to those on the Space Shuttle with placement based on FAMT control access requirement of Area 1. The pilot and commander each have a set of hand controllers due to the SRD redundant crew station system functions requirement.

Displays. The Lockheed Martin CEV configuration 503 baselined our current three display configuration per the results of a trade study (Lockheed Martin, 2006). The left hand display is primarily for the commander, the right hand display is primarily for the pilot, and the middle display is a shared display (Figure 8).

Display Controls. One anticipated display control is for a reversion switch (used to tell other systems that a display or display unit is not working correctly in situations where the

failure wasn't automatically detected). Other anticipated functionality is for a brightness/control switch. These controls were placed in control and display access Area 3 or better.

Fire Suppression. There are two placeholders that would allow the crew to extinguish fires manually, independent of an automation detected fire. The manual fire controls can be reached by crewmembers even when seated and were placed in control access Area 2 or better.

Electrical Power Routing and Inhibits. The CEV 604 configuration has placeholders for twenty Electrical Power System (EPS) circuit breakers. The placement of the circuit breakers will be revisited as the EPS design gets firmer.

Cabin Lights and Cabin Temperature Controls. The CEV 604 layout has one set of two dedicated cabin light controls and one dedicated temperature control, as a convenience to the crew due to anticipated frequency of use. The dedicated temperature control includes a display of current temperature and one of the current set point. Both controls were placed in control access Area 3 or better. We only provide one set of each control since we expect the crewmembers would also be able to control the cabin lighting and temperature using a cursor control device and the crew displays.

Communications. As with the EPS at the time of this configuration, we could only estimate crew communication needs from consultation with radio engineers. Placeholders are for band selection/band option and selecting antennae. The communications system was placed in control and display access Area 2 or better. We expect the crewmembers would also be able to control the communications system using a cursor control device and the crew displays.

Recovery Sequence and Pyro Event Manual Switches. The recovery sequence buttons are for emergency reentry in the case of a loss of primary power or RCS. While the needed functionality is not finalized, we have generic placeholders for anticipated functionality like Forward Backshell Pilot Chute, Jettison Forward Backshell, Drogue Chute Deploy, Main Chute Deploy, Main Chute Cut Away, and Float Bag Inflation. Other pyro event buttons might be for Jettison LAS, CM/SM Separation, Pressurize Backup RCS System, and Emergency Hatch Jettison. We also might have emergency re-entry initiation, pyro inhibits, and Environmental Control And Life Support System (ECLSS) mode selection controls in this area. Due to their criticality to safety of crew and spacecraft, these switches were placed in control access Area 1.

Center Control Panel. The center control panel is in control access Area 2 and display access Area 2. Functionality on this panel is generally expected to be very infrequently used or non-mission critical. The center control panel currently includes only the keyboard (see below).

Numeric/Alpha/Numeric Keyboard. The shared keyboard is provided for quicker entry of numbers or letters than with a virtual keyboard (on the screen). It is designed for gloved hand use and as such will not have all the keys of a standard QWERTY style keyboard. It is meant to be usable by either the commander or the pilot for short duration typing tasks and provides access to all the letters and numbers with four additional placeholders. For longer duration on-orbit tasks, it is assumed the crew will have access to full-fledged keyboards (on a laptop for instance). The anticipated keyboard design has individual numeric keypads for both commander and pilot. By providing individual numeric keypads, we reduce contention although the alpha keypad is still shared. In CEV 604, all portions of the shared keyboard are accessible to a seated HSIR minimum body size female.

DISCUSSION

The FAMT was used to derive the CEV 604 configuration console layout. The CEV 604 configuration was the baseline for Orion program. The configuration will change, as subsystem definitions and designs are matured, and as weight considerations may force tradeoffs and new configurations. The process outlined in this paper will be used for any further design work to re-design the displays and controls for new CEV configurations. In future iterations, we look to introduce some potential tool improvements.

The FAMT thresholds themselves may be an area of further investigation. Thresholds may differ between mission phase. Natural clusters could be uncovered that provide some guidance for the proper threshold. Failing a natural grouping of rankings, there may be factors beyond the rating that decide the area designation of a display or control.

Presently, the primary/secondary designation is based only on FAMT ratings. Engineering judgment should be used on the near-boundary cases to determine final designation. For instance, a navigation and trajectory task with a rating of [threshold-1] should probably be primary even though it is rated secondary. The FAMT-based ranking is an indicator of minimum need. It is always allowable to move to a higher level display.

ACKNOWLEDGEMENTS

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