Multi-Agent Systems : A Theory based on Organization and Communication concepts

Walid Chainbi

Laris laboratory-FSEG
FSEG B.P. 1088
3018 SFAX, TUNISIA
email: {Walid.Chainbi@fsegs.rnu.tn}

Abstract

This paper presents a theory for multi-agent systems based on communication concepts and organization concepts. The language of formulation is a first-order, multi-modal, linear-time logic. The underlying semantics of this language are labeled transition systems. An agent state is described by a triplet including beliefs, goals as communication concepts and roles as organization concepts. A transition consists of an execution step in the life-cycle of an agent. We illustrate our work with the well known prey/predator problem.

Introduction

M.Wooldridge and N.R.Jennings in (Wooldridge & Jennings 1994), identify three key issues related to multi-agent systems :

- *Agent theories* are essentially specifications. Agent theorists try to develop formalisms to formally represent and reason about the properties of agents.
- *Agent architectures* represent the move from specification to implementation. Those working in the area of agent architectures consider the issues surrounding the construction of computer systems that satisfy the properties specified by agent theorists.
- *Agent languages* are programming languages that allow one to program hardware or software computer systems in terms of some of the concepts developed by agent theorists.

The study presented in this paper is in keeping with the first theme of interest. In this regard, most known models in DAI use formalisms associated with logical systems including Cohen & Levesque (Cohen & Levesque 1990), Rao & Georgeff (Rao & Georgeff 1991). Their models are based on a possible world semantics where an agent's beliefs, knowledge, goals, and so on, are characterized as a set of so-called possible worlds, with an accessibility relation holding between them. These models suffer from the *omniscience* problem. Some alternative approaches have been adopted to avoid the problem of logical ominiscience. A commonly known alternative is the *syntactic approach*, in which what an agent knows is explicitly represented by a set of formulae in its knowledge base. This set is not constrained to be closed under logical consequence or to contain all instances of a given axiom scheme (Haddadi 1996). The *sentential approach* is more sophisticated than the syntactic approach, in that explicit beliefs are the primary beliefs and implicit beliefs are derived from them by closure under logical consequence (example : Konolige's deduction model (Konolige 1986)).
With respect to semantic models associated with multi-agent systems, another tendency has been revealed : Petri nets. Previously, Chainbi (Chainbi, Hannachi, & Sibertin-Blanc 1996) has used cooperative objects (a formalism which combines Petri nets and an object oriented approach) to model multi-agent systems. The marriage between the two approaches has given a great deal of flexibility to the system structuring. This flexibility is basically due to the advantages of the object oriented approach. Unfortunately, cooperative objects have a weak analytic power. Purvis (Purvis & Cranefield 1996) try to use colored Petri nets to model multi-agent systems but the proposed model remains at a high abstraction level. In this paper, we define a specification language which is a first-order, multi-modal and linear-time logic. We adopt the syntactic approach to avoid omniscience. Labeled transition systems are used as a semantic model associated to multi-agent systems(Chainbi, Jmaiel, & Hamadou 1998). The proposed semantics is the basis for the evaluation of our language formulae.

This paper is organised as follows : The syntax of the language is provided in section 2. Section 3 describes the semantics of the language which are given in four parts for simplification purpose : the preliminary of the language including the definition of the model within which formulae are evaluated is given in the first part ; the second part deals with the truth-conditions of temporal formulae ; the semantics of formulae which apply to actions and roles are described in the third part ; the modelling of beliefs and goals is mentioned in the fourth part.

The language syntax

$\mathcal{L}_W$ denotes the proposed specification language. In addition to the usual operators of first-order logic, $\mathcal{L}_W$ provides the temporal operators $\circ$(next time), $\Box$(always), $\mathcal{U}$(until), $\bullet$(previous), $\blacksquare$(always in the past), $\mathcal{S}$ (since); and modal operators for belief, goal and role, and a number of other operators that will be informally described below. The formulae $(\mathcal{B}\ x\ \varphi)$, $(\mathcal{G}\ x\ \varphi)$ and $(Has\_Role\ x\ r\ \varphi)$ mean : agent x has a belief φ, has a goal φ, and has a role r that if executed would achieve φ respectively.

Let L_f be the set of first-order logic formulae.

Definition 0.1 [$\mathcal{L}_W$ formulae]

$\mathcal{L}_W$ is defined as follows:

(i) $L_f \subseteq \mathcal{L}_W$;

(ii) if $\varphi \in \mathcal{L}_W$ then $\Box\ \varphi \in \mathcal{L}_W$, $\circ\ \varphi \in \mathcal{L}_W$, $\varphi\ \mathcal{U}\ \psi \in \mathcal{L}_W$, $\blacksquare\ \varphi \in \mathcal{L}_W$, $\bullet\ \varphi \in \mathcal{L}_W$, $\varphi\ \mathcal{S}\ \psi \in \mathcal{L}_W$;

(iii) if $\varphi, \psi \in \mathcal{L}_W$ then $\varphi \vee \psi\ \in\ \mathcal{L}_W$, $\neg\varphi\ \in\ \mathcal{L}_W$;

(iv) if $y \in X$ (the set of variables) and $\varphi \in \mathcal{L}_W$ then $\exists y \varphi \in \mathcal{L}_W$;

(v) if $x \in Ag$ (the set of agents), and $\varphi \in \mathcal{L}_W$ then $\mathcal{B}\ x\ \varphi\ \in\ \mathcal{L}_W$, $\mathcal{G}\ x\ \varphi\ \in\ \mathcal{L}_W$;

(vi) if $x \in Ag$ (the set of agents), $a \in Ac$ (the set of actions), $\varphi \in \mathcal{L}_W$, and r a role then $OCCURRED\ a\ \in\ \mathcal{L}_W$, $Agent\ x\ a\ \in\ \mathcal{L}_W$, $Has\_Role\ x\ r\ \varphi \in \mathcal{L}_W$.

The semantics

This section describes the truth conditions of $\mathcal{L}_W$ formulae. The semantics of first-order formulae is described as usual. Before we describe the model within which $\mathcal{L}_W$ formulae are evaluated.

The behavioral semantics

The model in which $\mathcal{L}_W$ formulae are evaluated is a labeled transition system. In this model, a multi-agent system is represented by a triplet $< \mathcal{S}, \mathcal{A}, \Omega >$ consisting of :

- a set $\mathcal{S}$ of states where each element describes the complete instantaneous state of the system ;
- a set $\mathcal{A}$ of actions : an agent can perform at a time point one of the following actions :
  - *physical* actions : are interactions between agents and the spatial environment,
  - *communicative* actions : are interactions between agents. They can be *emission* or *reception* actions,
  - *private* actions : are internal functions of an agent. They correspond to an agent exploiting its internal computational resources, and
  - *decision* action : can generate communicative, physical and private actions. A decision action can also update the agent's beliefs. We assume that the agent's goals are modified only after a negotiation with the other agents (see below).

The actions to execute are determined by the resolution methods and communication protocols. We denote by APH the set of physical actions, APR the set of private actions, ACO the set of communicative actions such that $ACO = ACOE \cup ACOR$ where $ACOE$ is the set of emission actions and $ACOR$ is the set of reception actions, τ a decision action, which an agent can execute.

We use *Roles* to denote the set of all possible roles.

$$Roles \stackrel{\text{def}}{=} Seq(APH \cup APR \cup ACO)$$

Where $Seq(E)$ denotes the set of all finite and infinite sequences of elements of E.

- a set Ω of all possible system executions which are finite or infinite sequences of the form

$$s_0 \xrightarrow{a_1} s_1 \xrightarrow{a_2} s_2 \ldots$$

where each s_i is a state and each a_i is an action.

Behavioral semantics of a single agent system
An agent state s_x is a triplet $< B_x, G_x, R_x >$ defined as follows : B_x is the set of beliefs of the agent x, G_x its goals, and R_x its role.

This making up of the agent state is justified by the following two points : On the first hand, no consensus has been reached in the DAI community regarding the components of the intentional state of an agent. Some studies adopt the concepts of beliefs, wants and intentions (example : Rao and Georgeff (Rao & Georgeff 1991)). Others contented themselves with beliefs, obligations and aptitudes (example : Shoham (Shoham 1993)). On the other hand, our approach is in keeping with *mass* [1] conception which emphasizes the study of interaction as a preliminary to deduce the intentional structure of agents(Chainbi, Jmaiel, & Hamadou 1998). Cooperation was our guiding line to deduce an agent model. Our study of cooperation(Chainbi 1997) had led us to deduce *roles* as organization concepts, *beliefs* and *goals* as concepts related to communication. To represent beliefs, we adopt the idea of Wooldridge (Wooldridge 1994) who represented beliefs by ground atoms of first-order logic. We represent an agent goal by a first-order formula. We assume that the sets of all possible beliefs and goals is finite since we deal with agents that have limited resources.

Definition 0.2 [The state transition due to an action]

Let $< B, G, R >$ be a state of an agent and a an action. The state transition due to a physical, private or communicative action is described by :

$$< B,\ G,\ a.R > \xrightarrow{a} < B',\ G,\ R > \text{ such that :}$$

[1] In contradiction with *individual* conception, the other standpoint adopted to design multi-agent systems which stresses the formal representation of an agent model (agents as intentional systems). Most theorists work along the lines of indivividual conception.

(i) if $a \in APH \cup APR \cup ACOR$ then $B' = (B - Bels_a(s)) \cup Bels'_a(s)$ where : $Bels_a(s)$ denotes the set of beliefs of the agent at a state s and on which the action a have an impact. This impact corresponds to the application of functions that is, if $Bels_a(s) = \{R_1(\ldots), \ldots, R_k(\ldots)\}$ then there is $f_1, \ldots, f_k$ such that $Bels'_a(s) = \{f_1(R_1(\ldots)), \ldots, f_k(R_k(\ldots))\}$.

(ii) if $a \in ACOE$ then $B' = B$

Example 0.3

Physical action

In the prey/predator game, *move_right* is a physical action which a predator is able to do. The ground atom $Position(self, v_1, v_2)$ is an agent's belief which indicates its position on the grid. Let $Bels_{move\_right}(s) = \{Position(self, v_1, v_2)\}$ and G a predator's goal (e.g. getting closer to a prey from the southern side). Let the predator's role = $< move\_right, move\_right, move\_up >= R$. Then, we have

$$< B, G, R > \stackrel{move\_right}{\longrightarrow} < B', G', R' > \text{ where :}$$

$B' = (B - \{Position(self, v_1, v_2)\}) \cup \{Inc\_Abs(Position(self, v_1, v_2))\} = (B - \{Position(self, v_1, v_2)\}) \cup \{Position(self, v_1 + 1, v_2)\}$ such that *Inc_Abs* is a function which increments the first component of the agent coordinates on the grid ;

$G' = G$; $R' =< move\_right, move\_up >$.

Private action

Let $Distance(self, prey, d)$ a ground atom denoting the distance separating the predator from the prey. Calculating this distance is done by the private action *distance_to_target*.

Let $Bels_{distance\_to\_target}(s) = \{Distance(self, prey, d)\}$. Let the agent's $role = < distance\_to\_target, move\_right, move\_up >$.

$$< B, G, R > \stackrel{distance\_to\_target}{\longrightarrow} < B', G', R' > \text{ where :}$$

$B' = (B - \{Distance(self, prey, d)\}) \cup \{f(Distance(self, prey, d))\}$ such that f is a function which updates the distance separating the prey and the predator ;

$G' = G$; $R' =< move\_right, move\_up >$.

Definition 0.4 [The state transition due to a decision action]

Let $< B, G, R >$ be a state of an agent and τ a decision action. The state transition due to the execution of a decision action is described by $< B, G, R > \stackrel{\tau}{\longrightarrow} < B', G, R' >$ such that :

(i) $B' = (B - Bels_\tau(s)) \cup Bels'_\tau(s)$

(ii) $R' = mod(R)$ where mod is an update function of the role resulting in the following operations :

- The generation of an action (physical, private or communicative). In this case, the action will be integrated in the role and $mod(R) = Insert(R, a)$. - Insert is a function which integrates the action a in the role R
- The suppression of an action (physical, private or communicative). In this case, $mod(R) = Delete(R, a)$. Delete is a function which deprives the role of one of its actions
- The repetition of the two operations mentioned above.

Behavioral semantics of a multi-agent system A multi-agent system state SA is a tuple $<< B_{x_1}, G_{x_1}, R_{x_1} >, \ldots, < B_{x_i}, G_{x_i}, R_{x_i} >, \ldots, < B_{x_n}, G_{x_n}, R_{x_n} >, GG >$ where : $< B_{x_i}, G_{x_i}, R_{x_i} >$ is the state of the agent x_i, and GG is the global goal of the system such that $\mathcal{R}\ (G_{x_1}, G_{x_2}, \ldots, G_{x_n}) \Longrightarrow GG$ where $\mathcal{R}$ is a relation which combines the local goals of the agents.

Note that $\mathcal{R}$ is closely related to the system to be modeled. For example, in the prey/predator problem, GG is the capture of the prey, G_{x_i} is getting closer to the prey from one side (north,west, east or south) and $\mathcal{R}$ is the conjunction of all the local goals.

Definition 0.5 [The state transition due to an action]

Let $<< B_{x_1}, G_{x_1}, R_{x_1} >, \ldots, < B_{x_i}, G_{x_i}, R_{x_i} >, \ldots, < B_{x_n}, G_{x_n}, R_{x_n} >, GG >$ be a state of our system, and let $A_i =< B_{x_i}, G_{x_i}, R_{x_i} >$ be a state of an agent x_i $(i : 1..n)$. The state transition due to an action is described by the following inference rules :

(i) $a \in APH \cup APR$

$$\frac{< B_{x_i}, G_{x_i}, a.R_{x_i} > \stackrel{a}{\longrightarrow} < B'_{x_i}, G_{x_i}, R_{x_i} >}{< A_1, \ldots, A_i, \ldots, A_n, GG > \stackrel{a}{\longrightarrow} < A_1, \ldots, < B'_{x_i}, G_{x_i}, R_{x_i} >, \ldots, A_n, GG >}$$

If an agent is ready to execute a physical or private action, then the whole system is ready to execute the same action.

(ii) $a \in ACOE, \bar{a} \in ACOR$

$$\frac{< B_{x_i}, G_{x_i}, a.R_{x_i} > \stackrel{a}{\longrightarrow} < B_{x_i}, G_{x_i}, R_{x_i} >; \quad < B_{x_j}, G_{x_j}, a.R_{x_j} > \stackrel{\bar{a}}{\longrightarrow} < B'_{x_j}, G_{x_j}, R_{x_j} >}{< A_1, \ldots, A_i, \ldots, A_n, GG > \stackrel{a\bar{a}}{\longrightarrow} < A_1, \ldots, < B_{x_i}, G_{x_i}, R_{x_i} >, \ldots, < B'_{x_j}, G_{x_j}, R_{x_j} >, \ldots, A_n, GG >}$$

If an agent is ready to send a message a and another agent is ready to receive the same message, then the whole system is ready, in this case, to execute this interaction. We note it by $a\bar{a}$(we model communication in a synchronous way).

(iii) τ a decision action

$$\frac{< B_{x_i}, G_{x_i}, R_{x_i} > \xrightarrow{\tau} < B'_{x_i}, G_{x_i}, R'_{x_i} >}{< A_1, \ldots, A_i, \ldots, A_n, GG > \xrightarrow{\tau} < A_1, \ldots, < B'_{x_i}, G_{x_i}, R'_{x_i} >, \ldots, A_n, GG >}$$

Each decision action executed by an agent changes the state of the system by changing the corresponding state of the decision-maker.

(iv) negotiation action : it is a finite sequence of communicative actions[2] initiated to update the goals of the agents. Indeed, under certain circumstances, it can be useful for an agent to modify his proper goal. We assume that the global goal can change if the agents perceive that it can't be achieved any longer. Let η be a negotiation action, we use the following axiom to describe its impact

$$< A_1, \ldots, A_i, \ldots, A_n, GG > \xrightarrow{\eta} < A'_1, \ldots, A'_i, \ldots, A'_n, GG' > \text{ where}$$

$A_i =< B_{x_i}, G_{x_i}, R_{x_i} >$; $A'_i =< B'_{x_i}, G'_{x_i}, R'_{x_i} >$ and $\mathcal{R}\ (G'_{x_1}, \ldots, G'_{x_i}, \ldots, G'_{x_n}) \Longrightarrow GG'$

The negotiation action is represented in the above definition (iv) at a high level of abstraction(a single action). Next we give some useful definitions for the semantics of $\mathcal{L}_W$ formulae described below.

Definition 0.6 [precedence relation on state sequence]

Let $\mathcal{M}$ be a state transition sequence, and $ST(\mathcal{M})$ be the set of states including the transitions of $\mathcal{M}$. We define the immediate successor of a state $s \in ST(\mathcal{M})$ by the relation $\prec$ such that :
$\forall s, s' \in ST(\mathcal{M}) : s \prec s'$ iff s' is the immediate successor of s in $\mathcal{M}$.
We denote by $\prec^*$ the reflexive and transitive closure of $\prec$.

The set of accessible states from a given state is defined as follows :

Definition 0.7 [The set of accessible states]

Let $\mathcal{M}$ be a state sequence. The set of accessible states from a given state s is defined as follows :
$\mathcal{A}(s) = \{s' \in ST(\mathcal{M}) | s \prec^* s'\}$

Semantics of temporal formulae

The semantics of temporal fromulae is given in a state sequence $\mathcal{M}$, with respect to a current time point s.

$< \mathcal{M}, s > \models \Box\, \varphi$ iff forall $s' \in \mathcal{A}(s)$, $< \mathcal{M}, s' > \models \varphi$

$< \mathcal{M}, s > \models \circ\, \varphi$ iff $< \mathcal{M}, s' > \models \varphi$ where $s \prec s'$

$< \mathcal{M}, s > \models \varphi\, \mathcal{U}\, \psi$ iff there is $s' \in \mathcal{A}(s)$ such that $< \mathcal{M}, s' > \models \psi$ and forall s'' $(s \prec^* s'' \prec^* s')$, $< \mathcal{M}, s'' > \models \varphi$

$< \mathcal{M}, s > \models \blacksquare\, \varphi$ iff forall s' such that $s' \prec^* s$, $< \mathcal{M}, s' > \models \varphi$

$< \mathcal{M}, s > \models \bullet\, \varphi$ iff $< \mathcal{M}, s' > \models \varphi$ where $s' \prec s$

$< \mathcal{M}, s > \models \varphi\, \mathcal{S}\, \psi$ iff there is s' such that $s' \prec^* s$ and $< \mathcal{M}, s' > \models \psi$, and forall s'' $(s' \prec^* s'' \prec^* s)$, $< \mathcal{M}, s'' > \models \varphi$

[2] Actually, the communicative actions used to negotiate are different from the usual communicative actions mentioned above. The latters cannot modify the goals whereas the formers are designed to update the agent goals.

Actions and roles

In this section, we give the semantics of action and role formulae.

Semantics of action formulae With respect to an action, it may be interesting to reason about its occurrence. Hence, we use the following operators which could be applied on actions : *ENABLED* and *OCCURRED*. Let a be an action, (*ENABLED* a) means that the action a is ready to be executed. (*OCCURRED* a) means that the action a has just been executed. The semantics of the occurrence of an action are given in a state sequence $\mathcal{M}$ and at a current time point s of $\mathcal{M}$:
$< \mathcal{M}, s > \models ENABLED\ a$ iff there is a state transition $s \xrightarrow{a} s'$ in $\mathcal{M}$
We can define $(OCCURRED\ a)$ in terms of $(ENABLED\ a)$: $(OCCURRED\ a) \stackrel{\text{def}}{=} \bullet(ENABLED\ a)$.
The fact that an action a is of an agent x, is denoted by the formula $(Agent\ x\ a)$ which semantics is given in a state sequence $\mathcal{M}$ as follows :
$< \mathcal{M}, s > \models Agent\ x\ a$ iff there is $s' \xrightarrow{a} s$ in $\mathcal{M}$ and $a \in EL(R_x)$
- R_x is the role of the agent x.
- $EL(Se)$ denotes the set of elements composing the sequence Se.
To denote that an agent x is ready to execute an action a, we use the following abbreviation :
$(ENABLED\ x\ a) \stackrel{\text{def}}{=} (Agent\ x\ a) \wedge (ENABLED\ a)$.
Similarly, we use the abbreviation $(OCCURRED\ x\ a)$ to denote that the agent x has just executed the action a. $(OCCURRED\ x\ a) \stackrel{\text{def}}{=} (Agent\ x\ a) \wedge (OCCURRED\ a)$.

Semantics of role formulae Each agent has a role denoting its organization component. A role is modelled as mentioned above by a sequence of actions. Next, we give the semantics of role formulae. The formula $(PERFORM\ x\ r)$ means that an agent x fills its role r and its semantics is given by the following rule :
$< \mathcal{M}, s > \models PERFORM\ x\ r$ iff there is s' such that $s \prec^* s'$, and forall $a \in EL(r)$, $< \mathcal{M}, s' > \models OCCURRED\ x\ a$
The past execution of a role r is denoted by the formula $\blacklozenge\ (PERFORM\ x\ r)$ which means that an agent x has filled his role r. We use the following abbreviation :
$(PERFORMED\ x\ r) \stackrel{\text{def}}{=} \blacklozenge\ (PERFORM\ x\ r)$.
We use the formula $(Has\_Role\ x\ r\ \varphi)$ to denote that an agent x has a role r to achieve φ.

The semantics of this formula is given in $\mathcal{M}$ and at a current time point s :

$< \mathcal{M}, s > \models Has\_Role\ x\ r\ \varphi$ iff

$< \mathcal{M}, s > \models \Box\ ((PERFORMED\, x\, r) \Rightarrow \varphi)$

We're also interested in knowing whether an agent would succeed to achieve φ. Let $(Succeeds\ x\ \varphi)$ be a formula denoting the success of an agent x to achieve φ. Formally :

$(Succeeds\ x\ \varphi) \stackrel{\text{def}}{=} \exists r \in Roles\ (Has\_Role\ x\ r\ \varphi)$

Example 0.8 [The achievement of a goal]
Let $\varphi \equiv \forall X\ \forall Y\ Position(prey, X, Y) \Longrightarrow Position(\alpha, X-1, Y)$ be the local goal of the predator α denoting getting closer to a prey from the western side. The achievement of φ is specified by the following formula : $\psi \equiv Succeeds\ \alpha\ \varphi$. Proving ψ requires that the agent has a role r to achieve φ $(Has\_Role\ \alpha\ r\ \varphi)$ and the agent succeeds to achieve φ.

Beliefs and goals

Beliefs are modelled by a finite set of ground atoms associated to each state. Similarly, goals are represented by a finite set of first-order logic formulae associated to each state. A belief formula is of the form $(\mathcal{B}\ x\ \varphi)$ and means that agent x has φ as a belief. A goal formula is $(\mathcal{G}\ x\ \varphi)$ and means that agent x has φ as a goal. The formal semantics of beliefs and goals are given in a state transition sequence $\mathcal{M}$ with respect to a current time point s.

$< \mathcal{M}, s > \models (\mathcal{B}\ x\ \varphi)$ iff $\mathcal{NF}(\varphi) \in B_x$

$< \mathcal{M}, s > \models (\mathcal{G}\ x\ \varphi)$ iff $\mathcal{NF}(\varphi) \in G_x$

According to the semantics of beliefs, a formula is said to be believed at a point time s by an agent if and only if its normal form (denoted by $\mathcal{NF}$) belongs to the set of its beliefs at this time point. This setting enables to reduce the set of beliefs [3] . The set of beliefs is time-dependent. Indeed, B may be different at a time point t_0 from the one at t_1. Thus, the agent can change his beliefs according to the semantics of the actions executed. Similarly, an agent is said having φ as a local goal (global respectively) if and only if its normal form belongs to the set of its goals at the time point s (all the time points respectively).

Conclusion

This paper has presented a specification language $\mathcal{L}_w$ for multi-agent systems which is first-order, multi-modal, linear-time logic. Unlike most theories where the authors use possible world semantics to deal with the truth-conditions of the formulae, $\mathcal{L}_w$ is based on labeled transition systems. The underlying agent model to our theory follows a mass conception. Indeed, starting from the study of cooperation in multi-agent systems, we identify the underlying concepts of an agent. These concepts consist of communication concepts and organization concepts. In future, we hope to extend the work presented in this paper in a number of ways. First, the underlying axiomatic system to $\mathcal{L}_w$ need to be developed -we are currently working at this level. Second, we should address the following question : given a specification φ, expressed in $\mathcal{L}_w$, how do we construct a system S such that S *satisfies* φ ? In this regard, we know that there are two general approaches in the literature : to directly execute φ, or compile φ into a directly executable form.

[3]In fact, we augment the set of beliefs without augmenting its reserved space.

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