1 Definition

1.1 Defintion

Let prop be a set of variables. Then a formula ϕ is defined as follows :

$$\phi ::= p \mid \bot \mid \phi \mid \phi \rightarrow \phi \mid \Box_i \phi$$

where $p \in Prop$ and $\Box_i$ is a modal operator. Other connectives are expressed through $\bot$ and $\rightarrow$ and dual modal operators $\diamond_i$ as $\diamond_i \phi = \neg \Box_i \neg \phi$

1.2 Defintion

A normal modal logic is a set of modal formulas containing all propositional tautologies, closed under Substitution ($\frac{\phi(p_i)}{\phi(\psi)}$), Modus Ponens ($\frac{\phi, \phi \rightarrow \psi}{\psi}$), Generalization rules ($\frac{\phi}{\Box_i \phi}$) and the following axioms

$$\Box_i(p \rightarrow q) \rightarrow (\Box_i p \rightarrow \Box_i q)$$

K_n denotes the minimal normal modal logic with n modalities and $K = K_1$ Let L be a logic and let Γ be a set of formulas. Then L+Γ denotes the minimal logic containing L and Γ

1.3 Definition

Let L1 and L2 be two modal logic with one modality $\Box$. Then the fusion of these logics are defined as follows :

$$L1 \otimes L2 = K2 + L_{1(\Box \rightarrow \Box_1)} L_{2(\Box \rightarrow \Box_2)}$$

The follow logics may be important

$$D = K + \Box p \rightarrow \Diamond p$$

$$T = K + \Box p \rightarrow p$$

$$D4 = D + \Box p \rightarrow \Box\Box p$$

$$S4 = T + \Box p \rightarrow \Box\Box p$$

2 Kripke Definition

To show D $\otimes$ D $\otimes$ D + $\Box p \to \Box_1 p \wedge \Box_2 p$ has the finite model property, we need some important defintions.

2.1 Defintion

Let $M = (W, R, V)$ be a model and $w \in W$ a state in M. The notion of a formula being true at w is inductively defined as follows :

$$M, w \Vdash \Box\phi \text{ iff } \forall v \in W : wRv \to M, v \Vdash \phi$$

This defintion can be extended to a multimodal version, where the modal operators are interpreted the same way but with the respective relation.

2.2 Defintion

A set Σ is closed under subformulas, if for all formulas ϕ and ϕ' the following holds :

1. if $\neg\phi \in \Sigma$ then $\phi \in \Sigma$
2. if $\phi \vee \phi' \in \Sigma$ then $\phi, \phi' \in \Sigma$
3. if $\Box\phi \in \Sigma$ then $\phi \in \Sigma$

We can define it similary for a multimodal logic. For every modal operator $\Box_n$, we extend this definition by adding a new condition similar to the third. Example : Suppose we have a multimodal logic with $\Box, \Box_1$ called $L_{\Box,\Box_1}$ and $\phi = \Box p \to \Box_1 q$ and $\phi \in \Sigma$. Then $\Sigma = \{\phi, \neg\Box p, \Box_1 q, \Box p, p, q\}$ is closed under subformulas.

2.3 Defintion

Let $M = (W, R, V)$ be a model and suppose Σ is a set of formulas. We define a relation $\equiv$ on W as follows :

$$w \equiv v \text{ iff } \forall\phi \in \Sigma : M, w \Vdash \phi \Leftrightarrow M, v \Vdash \phi$$

It is well known that the $\equiv$-relation is an equivalence relation. We denote the equivalence class of a state $w \in W$ as $[w]_\Sigma = \{v \mid v \equiv w\}$. Furthermore W_Σ is the set of all equivalence classes, i.e $W_\Sigma = \{[w]_\Sigma \mid w \in W\}$.

2.4 Defintion

Let $M = (W, R, V)$ be a model, Σ is closed under subformulas and W_Σ the set of equivalence classes induced by $\equiv$. A model $M^f_\Sigma = (W^f, R^f, V^f)$ is called filtration of M through Σ if the following holds :

1. $W^f = W_\Sigma$
2. If $(w, v) \in R$ then $([w], [v]) \in R^f$
3. If $([w], [v]) \in R^f$ then for any $\Box\phi \in \Sigma$: if $M, w \Vdash \Box\phi$ then $M, v \Vdash \phi$
4. $V^f = \{[w] \mid M, w \Vdash p\}$, for all propositional variables $p \in \Sigma$

In our case, we are in a multimodal logic with three modal operators $\Box, \Box_1, \Box_2$. We need to extend this defintion for $L_{\Box,\Box_1,\Box_2}$. This means our model looks like: $M = (W, R, R_1, R_2, V)$. We extend the conditions as follows :

If $(w, v) \in R_i$ then $([w], [v]) \in R^f_i$
If $([w], [v]) \in R^f_i$ then for any $\Box_i\phi \in \Sigma$: if $M, w \Vdash \Box_i$ then $M, v \Vdash \phi$, where $i \in \{1, 2\}$

2.5 Filtration Theorem

Consider $L_{\Box,\Box_1,\Box_2}$. Let $M^f = (W_\Sigma, R^f, R^f_1, R^f_2, V)$ be a filtration of M through a subformula closed set Σ. Then for all formulas $\phi \in \Sigma$, and all nodes $w \in M$, we have

$$M, w \Vdash \phi \text{ iff } M^f, [w] \Vdash \phi$$

Proof. By induction on ϕ. We will only show non-trivial and, for our purposes, necessary cases.

Case $\phi = p$: Left to right follows immediately from filtration defintion. Conversely, suppose $M^f, [w] \Vdash p$. This means $[w] \in V^f(p)$. But this means V(p) can not be empty. Pick any $v \in V(p)$. Obviously, $w \equiv v$ and $M, v \Vdash p$. Hence, $M, w \Vdash p$.

Case $\phi = \neg\psi$: Suppose ψ holds. Then we have : $M, w \Vdash \phi$ iff $M, w \nVdash \psi$. Applying induction hypothesis, we get : $M^f, [w] \nVdash \psi$. But then, we have $M^f, [w] \Vdash \phi$. Right to left is the same.

Case $\phi = \phi_1 \wedge \phi_2$: Suppose ϕ_1, ϕ_2 holds. Let $M, w \Vdash \phi$. That means $M, w \Vdash \phi_1$ and $M, w \Vdash \phi_2$. Applying induction hypothesis, we get $M^f, [w] \Vdash \phi_1$ and $M^f, [w] \Vdash \phi_2$. But then, $M^f, [w] \Vdash \phi_1 \wedge \phi_2 = \phi$. Right to left is similar.

Case $\phi = \Box_i\psi$ ($i \in \{1, 2, \epsilon\}, \Box_\epsilon = \Box$): Left to right. Suppose ψ holds and $M, w \Vdash \Box_i\psi$. We need to show $M^f, [w] \Vdash \Box_i\psi$, this means $\forall[v] \in W_\Sigma : [w]R_i[v] \to M^f, [v] \Vdash \Box_i\psi$. Pick any $[v] \in W_\Sigma$ s.t $[w]R_i[v]$. By condition 3, w.r.t to the modal operator, we have $M, v \Vdash \psi$. By induction hypothesis, we get $M^f, [v] \Vdash \psi$. Because [v] was arbitrary it follows that $M^f, [w] \Vdash \Box_i\psi$.

Right to left. Suppose ψ holds and $M^f, [w] \Vdash \Box_i\psi$. Pick $v \in W$ s.t wR_iv. By condition 2, w.r.t to the modal operator, we have $[w]R_i^f[v]$. So, $M^f, [v] \Vdash \psi$. By induction hypothesis, we get $M, v \Vdash \psi$. Because v was arbitrary, we have $M, w \Vdash \Box_i\psi$.

$\Box$

Now define the smallest filter for $L_{\Box,\Box_1,\Box_2}$ and show that this is a filter. We denote this as R^s.

2.6 Defintion

Let $M = (W, R, V)$ be a model, Σ is closed under subformulas and W_Σ the set of equivalence classes. We define :

$$R^s = \{[w], [v] \mid \exists w' \in [w], \exists v' \in [v] : w'R_iv'\}$$

where $i \in \{1, 2, \epsilon\}$.

2.7 Lemma

Let $M = (W, R, V)$ be a model, Σ is closed under subformlas and W_Σ the set of equivalence classes induced by $\equiv$ and V^f the standard valuation on W_Σ. Then $(W_\Sigma, R^s, R_1^s, R_2^s, V^f)$ is a filtration of M through Σ.

Proof. It suffices to show R_i^s fullfills the condition 2 and 3 w.r.t to the corresponding modal operator $\Box_i$. But R_i^s already satisfies condition 2. Let's check the other condition. Let $\Box_i\phi \in \Sigma$, $[w]R_i^s[v]$ and $M, w \Vdash \Box_i\phi$ where $i \in \{1, 2, \epsilon\}$. Because of $[w]R_i^s[v]$ we pick a $w' \in [w]$ and $v' \in [v]$. By defintion, we have $w'R_iv'$. Because $w' \equiv w$, we get $M, w' \Vdash \Box_i\phi$. Hence, $M, v' \Vdash \phi$ and by $v' \equiv v$, we get $M, v \Vdash \phi$.

$\Box$

2.8 Proposition

Let Σ be a finite subformula closed set of $L_{\Box,\Box_1,\Box_2}$. For any model M, if M^f is a filtration through Σ, then M^f contains at most 2^n nodes (where n denotes the size of Σ).

Proof. The states of M^f are the equivalence classes in W_Σ. Let $g : W_\Sigma \to P(\Sigma)$ defined by $g([w]) = \{\phi \in \Sigma \mid M, w \Vdash \phi\}$. g is well defined. Pick any u and v s.t $u \equiv v$. But then by defintion of $\equiv$, they fullfill the same subformulas. This means g([v]) = g([u]).
g is also injective. Pick any $[u], [v] \in W_\Sigma$ s.t g([u]) = g([v]). We show $[u] \subseteq [v]$. The other inclusion is similar. By assumption we have $u \equiv v$. Pick any $u' \in [u]$. Then we have $u' \equiv u \equiv v$. Hence, $u' \in [v]$. At the end, this means M^f contains at most 2^n nodes. $\Box$

2.9 Finite Model Property - via Filtrations

Let ϕ be a formula of $L_{\Box,\Box_1,\Box_2}$. If ϕ is satisfiable, then it is satisfiable on a finite model containing at most 2^n nodes, where n is the number of subformulas in ϕ.

Proof. Assume that ϕ is satisfiable on a model on M. Take any filtration of M through the set of subformulas of ϕ. By Filtration Theorem, we get that ϕ is satisfied in the filtration model M^f. Furthermore, it is bounded by 2^n.

$\Box$

Now we define Sahlqvist formulas for our purposes.

2.10 Defintion

A modal formula ϕ is positive if all variables occurs without negation. In the other hand, a formula is negative, if all variables occurs with negation. A boxed atom is a modal formula of the form $\Box^n p$ for some $n \in \mathbb{N}$, where p is a propositional variable and $\Box^n p$ is defined as follows : $\Box^0 p = p$, $\Box^1 p = \Box p$, $\Box^{n+1} p = \Box(\Box^n p)$.

Furthermore, a Sahlqvist antecedent is built from $\bot, \top$, negative formulas and boxed atoms by applying $\Diamond$ and $\wedge$. A Sahlqvist implication is a modal formula of the form $\phi \to \psi$, where ϕ is a Sahlqvist antecedent and ψ a positive formula.
Now, a Sahlqvist formula is built from Sahlqvist implications by applying $\Box$ and $\vee$.

Examples for Sahlqvist formulas:

$$\Box\Box p \to \Box p$$

$$\Diamond\neg p \to p$$

$$\Diamond\Box\Box\Box\Box\Box p \to \Box\Diamond\Box\Diamond p$$

$$\Box\Box\Box\Box(\Diamond\Box p \to p) \vee \Box\Box p \to \Box p$$

Non Sahlqvist Formulas :

$$\Box\Diamond p \to \Diamond\Box p$$

$$\Diamond\Box p \to \Box\neg p$$

We can extend this defintion for our logic. We say a boxed atom can also be $\Box_1^n p$ and $\Box_2^n p$. A Sahlqvist antecedent can also be build by applying $\Diamond_1$ and $\Diamond_2$. A Sahlqvist formula can be build by Sahlqvist implications by applying additionally $\Box_1$ and $\Box_2$.

3 Topological Space Defintion

3.1 Defintion

A topological space is a pair (X, τ) where τ is a collection of subsets of X (elements of τ are also called open sets) such that :

1. the empty set $\emptyset$ and X are open
2. the union of an arbitrary collection of open sets is open
3. the intersection of finite collection of open sets is open

The space is called Alexandroff, if we allow the intersection of infinite collection of open sets. A topological model is a structure M = (X,τ,v) where (X,τ) is a topological space and v is a valuation assigining subsets of X to propositional variables.

3.2 Defintion

Let M = (X,τ,v) a topological model and $x \in X$. The satisfaction of a formula at the point x in M is defined inductively as follows :
$M, x \models \Box\phi$ iff $\exists U \in \tau$ s.t $x \in U$ and $\forall u \in U : M, u \models \phi$
$M, x \models \Diamond\phi$ iff $\forall U \in \tau$ s.t $x \in U$ and $\exists u \in U : M, u \models \phi$

3.3 Defintion

Let $A = (X, \chi)$ and B =(Y, υ) be topological spaces. The standard product topology τ is the set of subsets of $X \times Y$ such that $X \in \chi$ and $Y \in \upsilon$.
Let $N \subseteq X \times Y$. We call N horizontally open if $\forall (x, y) \in N\ \exists U \in \chi : x \in U$ and $U \times \{y\} \subseteq N$.
We call N vertically open if $\forall (x, y) \in N\ \exists V \in \upsilon : y \in V$ and $\{x\} \times V \subseteq N$
If N is H-open and V-open, then we call it HV-open.
We denote τ_1 is the set of all H-open subsets of $X \times Y$ and τ_2 is the set of all V-open subsets of $X \times Y$

3.4 Defintion

Let X and Y be topological spaces and $f : X \to Y$ a function. We call f continuous if for each open set $U \subseteq Y$ the set $f^{-1}(U)$ is open in X. We say f is open if for each open set $V \subseteq X$ the set f[V] is open in Y.

3.5 Remark

There is an alternative defintion for open sets. Let (X,τ) be a topological space and U a set. U is open iff $\forall x \in U\ \exists V \subseteq U$: V is open and $x \in V$. This is true because, the union of open sets is an open set.

Now we define some Kripke frames, which we will use through this chapter.

3.6 Defintion

Let T_2 be the infinite binary tree with reflexive and transitive descendant relation.
Formally it is defined as follows : $T_2 = (W, R)$ where W = {0,1}* and sRt iff $\exists u \in W$: $s * u = t$.
The $T_{6,2,2}$ tree is the infinite six branching tree, where all nodes of $T_{6,2,2}$ is R-related, the first two R1-related and the last two R2-related. Formally we can define this tree as follows : $T_{6,2,2} = (W, R, R_1, R_2)$, where W = {0,1,2,3,4,5}*,

$$sRt \text{ iff } \exists u \in \{0,1,2,3,4,5\}^* : s * t = u$$

$$sR_1t \text{ iff } \exists u \in \{0,1\}^* : s * t = u$$

$$sR_2t \text{ iff } \exists u \in \{5,6\}^* : s * t = u$$

where s and t are elements of the set where the element u can come from, w.r.t to the relation. For example in the case sRt, s and t are elements of {0,1,2,3,4,5}*.

4 Neighbourhood

4.1 Defintion

Let X be a non-empty set. A function $\tau : X \to 2^{2^X}$ is called a neighbourhood function. A pair F = (X,τ) is called a neighbourhood frame (or n-frame). A model based on F is a tuple (X,τ,v), where v assigns a subset of X to a variable

4.2 Defintion

Let M =(X,τ,v) be a neighourhood model and x $\in$ X. The truth of a formula is defined inductively as follows :

$$M, x \models \Box\phi \text{ iff } \exists V \in N(x) \forall y \in V : M, y \models \phi$$

A formula is valid in a n-model M if it is valid at all points of M ($M \models \phi$). Formula is valid in a n-frame F if it is valid in all models based on F (notation $F \models \phi$). For Logic L we write $F \models L$, if for any $\phi \in L, F \models \phi$. We define nV(L) = $\{F \mid F \text{ is an n-frame and } F \models \phi\}$.

4.3 Defintion

Let F = (W,R) be a Kripke frame. We define an n-frame N(F) = (W, τ) as follows. For any $w \in W$ we have :

$$\tau(w) = \{U \mid R(w) \subseteq U \subseteq W\}$$

4.4 Defintion

Let X = (X, τ_1,...) and Y = (Y, σ_1,...) be n-frames. Then the function f: $X \to Y$ is called bounded morphism if

1. f is surjective
2. $\forall x \in X \, \forall U \in \tau_i(x) : f(U) \in \sigma_i(f(x))$
3. $\forall x \in X \, \forall V \in \sigma_i(f(x)) \, \exists U \in \tau_i(x) \, : f(U) \subseteq V$

4.5 Defintion

Let $X = (\mathrm{X}, \tau_1)$ and $Y = (\mathrm{Y}, \tau_2)$ be two n-frames. Then the product of these two frames is an n-2-frame and is defined as follows :

$$X \times Y = (\mathrm{X} \times \mathrm{Y}, \tau_1', \tau_2')$$
$$\tau_1'(x, y) = \{U \subseteq \mathrm{X} \times \mathrm{Y} \mid \exists V \in \tau_1(x) : V \times \{y\} \subseteq U\}$$
$$\tau_2'(x, y) = \{U \subseteq \mathrm{X} \times \mathrm{Y} \mid \exists V \in \tau_2(y) : \{x\} \times V \subseteq U\}$$

4.6 Defintion

For two unimodal logics L_1 and L_2 we define the n-product of them as follows :

$$L_1 \times_n L_2 = Log(\{X \times Y \mid X \in nV(L_1) \text{ and } Y \in nV(L_2)\})$$

Now we define some Kripke frames we need for this chapter.

4.7 Defintion

Let $T_{\omega[in]}$ (i = irreflexiv, n = non-transitiv) denote the infinite branching and infinite depth tree, which is irreflexiv and non-transitive. Formally the tree can be defined as : $T_{\omega[in]} = (W, R)$ where $W = \mathbb{N}^*$ and sRt iff $\exists u \in \mathbb{N} : s * u = t$ (the '*' is the concatenation operator)

The $T_{\omega,\omega,\omega[in]}$ tree is similary defined as the $T_{6,2,2}$ tree but with infinite branching and infinite depth. Before characterizing it, we say $\mathbb{N}_{R1}{}^*$ is the set of finite number combinations which has a subscript R_1 to denote that these numbers relate to R_1 (examples : $0_{R1}, 0123_{R1}$). $\mathbb{N}^+_{R_1}$ is the set $\mathbb{N}_{R_1}{}^*$- $\{\epsilon\}$. $\mathbb{N}^+_R$, $\mathbb{N}^+_{R_2}$ are defined similar.

Now let $T_{\omega,\omega,\omega[in]} = (W, R, R_1, R_2)$ where $W = \mathbb{N}^+_R \cup \mathbb{N}^+_{R_1} \cup \mathbb{N}^+_{R_2} \cup \{\epsilon\}$,

$$sRt \text{ iff } \exists u \in \mathbb{N}_R \cup \mathbb{N}_{R_1} \cup \mathbb{N}_{R_2} : s * u = t$$

$$sR_1t \text{ iff } \exists u \in \mathbb{N}_{R_1} : s * u = t$$
$$sR_2t \text{ iff } \exists u \in \mathbb{N}_{R_2} : s * u = t$$

where s,t are elements of the positive closure set where the element u can come from (additionally s can be ϵ), w.r.t to the relation. For example if we consider sR_1t, then $s, t \in \mathbb{N}^+_{R_1}$ but also $s = \epsilon$. Of course the '*' operator acts here again as a concatenation operator.