Reference Sheet for Discrete Maths

Propositional Calculus

Order of decreasing binding power: $=, \neg, \wedge/\vee, \Rightarrow/\Leftarrow, \equiv/\not\equiv$.

Equivales is the only equivalence relation that is associative $((p \equiv q) \equiv r) \quad \equiv \quad (p \equiv (q \equiv r))$, and it is symmetric and has identity true.

Discrepancy (difference) '$\not\equiv$' is symmetric, associative, has identity 'false', mutually associates with equivales $((p \not\equiv q) \equiv r) \quad \equiv \quad (p \not\equiv (q \equiv r))$, and mutually interchanges with it as well $(p \not\equiv q \equiv r) \quad \equiv \quad (p \equiv q \not\equiv r)$. Finally, negation commutes with difference: $\neg(p \equiv q) \equiv \neg p \equiv q$.

Implication has the alternative definition $p \Rightarrow q \;\equiv\; \neg p \vee q$, thus having true as both left identity and right zero; it distributes over $\equiv$ in the second argument, and is self-distributive; and has the properties:

Shunting $p \wedge q \Rightarrow r \;\equiv\; p \Rightarrow (q \Rightarrow r)$

Contrapositive $p \Rightarrow q \quad \equiv \quad \neg q \Rightarrow \neg p$

Leibniz $e = f \;\Rightarrow\; E[z \coloneqq e] = E[z := f]$

Modus Ponens

$$p \wedge (p \Rightarrow q) \quad \equiv \quad p \wedge q$$
$$p \wedge (q \Rightarrow p) \quad \equiv \quad p$$
$$p \wedge (p \Rightarrow q) \quad \Rightarrow \quad q$$

It is a *linear* order relation generated by 'false $\Rightarrow$ true'; whence "from false, follows anything": false $\Rightarrow p$. Moreover it has the useful properties "(3.62) Contextualisation": $p \Rightarrow (q \equiv r) \quad \equiv \quad p \wedge q \quad \equiv \quad p \wedge r$ —we *have* the context p in each side of the equivalence— and $p \Rightarrow (q \Rightarrow r) \quad \equiv \quad p \wedge q \;\Rightarrow\; p \wedge r$. Implication is "Sub-associative": $((p \Rightarrow q) \Rightarrow r) \;\Rightarrow\; (p \Rightarrow (q \Rightarrow r))$. Finally, we have "$\equiv$-$\equiv$ Elimination": $(p \equiv q \equiv r) \Rightarrow s \;\equiv\; p \Rightarrow s \;\equiv\; q \Rightarrow s \;\equiv\; r \Rightarrow s$.

Conjunction and disjunction distribute over one another, are both associative and symmetric, $\vee$ has identity false and zero true whereas $\wedge$ has identity true and zero false, $\vee$ distributes over $\vee, \equiv, \wedge, \Rightarrow, \Leftarrow$ whereas $\wedge$ distributes over $\equiv - \equiv$ in that $p \wedge (q \equiv r \equiv s) \;\equiv\; p \wedge q \quad \equiv \quad p \wedge r \quad \equiv \quad p \wedge s$, and they satisfy,

Excluded Middle	**Contradiction**	**Absorption**	**De Morgan**
$p \vee \neg p$	$p \wedge \neg p \equiv$ false	$p \wedge (q \vee \neg p) \equiv p \wedge q$	$\neg(p \wedge q) \equiv \neg p \vee \neg q$
		$p \vee (q \vee \neg p) \equiv p \vee q$	$\neg(p \vee q) \equiv \neg p \wedge \neg q$

Most importantly, they satisfy the **"Golden Rule"**: $p \wedge q \equiv p \equiv q \equiv p \vee q$.

The many other properties of these operations —such as weakening laws and other absorption laws and case-analysis ($\sqcup$-char)— can be found by looking at the list of *lattice properties* —since the Booleans are a lattice.

Orders

An *order* is a relation $\_ \sqsubseteq \_ : \tau \to \tau \to \mathbb{B}$ satisfying the following three properties:

Reflexivity	**Transitivity**	**Mutual Inclusion**
$a \sqsubseteq a$	$a \sqsubseteq b \wedge b \sqsubseteq c \Rightarrow a \sqsubseteq c$	$a \sqsubseteq b \wedge b \sqsubseteq a \;\equiv\; a = b$

Indirect Inclusion is like 'set inclusion' and Indirect Equality is like 'set extensionality'.

Indirect Equality (from above)
$x = y \;\equiv\; (\forall z \bullet x \sqsubseteq z \equiv y \sqsubseteq z)$

Indirect Inclusion (from above)
$x \sqsubseteq y \;\equiv\; (\forall z \bullet y \sqsubseteq z \Rightarrow x \sqsubseteq z)$

Indirect Equality (from below)
$x = y \;\equiv\; (\forall z \bullet z \sqsubseteq x \equiv z \sqsubseteq y)$

Indirect Inclusion (from below)
$x \sqsubseteq y \;\equiv\; (\forall z \bullet z \sqsubseteq x \Rightarrow z \sqsubseteq y)$

An order is *bounded* if there are elements $\top, \bot : \tau$ being the lower and upper bounds of all other elements:

Top Element	$a \sqsubseteq \top$	**Bottom Element**	$\bot \sqsubseteq a$
Top is maximal	$\top \sqsubseteq a \;\equiv\; a = \top$	**Bottom is minimal**	$a \sqsubseteq \bot \;\equiv\; a = \top$

Lattices

A *lattice* is a pair of operations $\_ \sqcap \_, \_ \sqcup \_ : \tau \to \tau \to \tau$ specified by the properties:

$\sqcup$-Characterisation
$a \sqsubseteq c \wedge b \sqsubseteq c \;\equiv\; a \sqcup b \;\sqsubseteq\; c$

$\sqcap$-Characterisation
$c \sqsubseteq a \wedge c \sqsubseteq b \;\equiv\; c \;\sqsubseteq\; a \sqcap b$

The operations act as providing the greatest lower bound, 'glb', 'supremum', or 'meet', by $\sqcap$; and the least upper bound, 'lub', 'infimum', or 'join', by $\sqcup$.

Let $\square$ be one of $\sqcap$ or $\sqcup$, then:

Symmetry of $\square$	**Associativity of $\square$**	**Idempotency of $\square$**
$a \square b \;=\; b \square a$	$(a \square b) \square c \;=\; a \square (b \square c)$	$a \square a \;=\; a$

Zero of $\square$	**Identity of $\square$**	**Absorption**	**Self-Distributivity of $\square$**
$a \sqcup \top = \top$	$a \sqcup \bot = a$	$a \sqcap (b \sqcup a) = a$	$a \square (b \square c) \;=\; (a \square b) \square (a \square c)$
$a \sqcap \bot = \bot$	$a \sqcap \top = a$	$a \sqcup (b \sqcap a) = a$	

Weakening / Strengthening
$a \;\sqsubseteq\; a \sqcup b$
$a \sqcap b \;\sqsubseteq\; a$
$a \sqcap b \;\sqsubseteq\; a \sqcup b$

Induced Defs. of Inclusion
$a \sqsubseteq b \;\equiv\; a \sqcup b \;=\; b$
$a \sqsubseteq b \;\equiv\; a \sqcap b \;=\; a$

Golden Rule
$a \sqcap b \;=\; a \quad \equiv \quad b = a \sqcup b$
$a \sqcap b \;=\; a \sqcup b \quad \equiv \quad a = b$
$a \sqcup b \;\sqsubseteq\; a \sqcap b \quad \equiv \quad a = b$

Monotonicity of $\square$
$a \sqsubseteq b \wedge c \sqsubseteq d \;\Rightarrow\; a \square c \;\sqsubseteq\; b \square d$

Duality Principle:

If a statement S is a theorem, then so is $S[(\sqsubseteq, \sqcap, \sqcup, \top, \bot) := (\sqsupseteq, \sqcup, \sqcap, \bot, \top)]$.

Conditionals

"If to $\wedge$" may be taken as axiom from which we may prove the remaining 'alternative definitions' "if to $\cdots$".

if to $\wedge$	$P[z \coloneqq \mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}]$	$\equiv$	$(b \Rightarrow P[z \coloneqq x]) \wedge (\neg b \Rightarrow P[z := x])$
if to $\vee$	$P[z \coloneqq \mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}]$	$\equiv$	$(b \wedge P[z \coloneqq x]) \vee (\neg b \wedge P[z := x])$
if to $\not\equiv$	$P[z \coloneqq \mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}]$	$\equiv$	$b \wedge P[z \coloneqq x] \not\equiv \neg b \wedge P[z := x]$
if to $\equiv$	$P[z \coloneqq \mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}]$	$\equiv$	$b \Rightarrow P[z \coloneqq x] \equiv \neg b \Rightarrow P[z := x]$

Note that the "$\equiv$" and "$\not\equiv$" rules can be parsed in multiple ways since '$\equiv$' is associative, and '$\equiv$' mutually associates with '$\not\equiv$'.

if true	$\mathsf{if\ true\ then}\ x\ \mathsf{else}\ y\ \mathsf{fi} = x$
if false	$\mathsf{if\ false\ then}\ x\ \mathsf{else}\ y\ \mathsf{fi} = y$
then true	$\mathsf{if}\ R\ \mathsf{then\ true\ else}\ P\ \mathsf{fi} = R \vee P$
then false	$\mathsf{if}\ R\ \mathsf{then\ false\ else}\ P\ \mathsf{fi} = \neg R \wedge P$
else true	$\mathsf{if}\ R\ \mathsf{then}\ P\ \mathsf{else\ true\ fi} = R \Rightarrow P$
else false	$\mathsf{if}\ R\ \mathsf{then}\ P\ \mathsf{else\ false\ fi} = R \wedge P$

if swap	$\mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi} = \mathsf{if}\ \neg b\ \mathsf{then}\ y\ \mathsf{else}\ x\ \mathsf{fi}$
if idempotency	$\mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ x\ \mathsf{fi} = x$
if guard strengthening	$\mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi} = \mathsf{if}\ b \wedge x \neq y\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}$
if Context	$\mathsf{if}\ b\ \mathsf{then}\ E\ \mathsf{else}\ F\ \mathsf{fi} = \mathsf{if}\ b\ \mathsf{then}\ E[b \coloneqq \mathsf{true}]\ \mathsf{else}\ F[b \coloneqq \mathsf{false}]\ \mathsf{fi}$
if Distributivity	$P[z \coloneqq \mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}] = \mathsf{if}\ b\ \mathsf{then}\ P[z \coloneqq x]\ \mathsf{else}\ P[z \coloneqq y]\ \mathsf{fi}$
if junctivity	$\big(\mathsf{if}\ b\ \mathsf{then}\ x\ \mathsf{else}\ y\ \mathsf{fi}\big) \oplus \big(\mathsf{if}\ b\ \mathsf{then}\ x'\ \mathsf{else}\ y'\ \mathsf{fi}\big) = \mathsf{if}\ b\ \mathsf{then}\ (x \oplus x')\ \mathsf{else}\ (y \oplus y')\ \mathsf{fi}$

Converse

Co-distributivity	$(x;y)^\smile = y^\smile ; x$
$^{\smile\smile}$, Involutive	$x^{\smile\smile} = x$
Monotonicity	$x \sqsubseteq y \Rightarrow x^\smile \sqsubseteq y^\smile$
Connection	$a^\smile \sqsubseteq b \equiv a \sqsubseteq b^\smile$
Elimination	$x^\smile = y^\smile \equiv x = y$

Named Properties

univalent	x	$\equiv$	$x^\smile ; x \sqsubseteq \mathsf{Id}$
surjective	x	$\equiv$	$\mathsf{Id} \sqsubseteq x^\smile ; x$
total	x	$\equiv$	$\mathsf{Id} \sqsubseteq x ; x^\smile$
injective	x	$\equiv$	$x ; x^\smile \sqsubseteq \mathsf{Id}$
mapping	x	$\equiv$	$\mathsf{total}\ x \wedge \mathsf{univalent}\ x$
bijective	x	$\equiv$	$\mathsf{surjective}\ x \wedge \mathsf{injective}\ x$
iso	x	$\equiv$	$\mathsf{mapping}\ x \wedge \mathsf{bijective}\ x$

Duality theorems

$\mathsf{univalent}\ (x^\smile) \equiv \mathsf{injective}\ x$

$\mathsf{total}\ (x^\smile) \equiv \mathsf{surjective}\ x$

$\mathsf{mapping}\ (x^\smile) \equiv \mathsf{bijective}\ x$

$\mathsf{iso}\ (x^\smile) \equiv \mathsf{iso}\ x$

Invertiblility theorems

$\mathsf{total}\ x \wedge \mathsf{injective}\ x \Rightarrow x ; x^\smile = \mathsf{Id}$

$\mathsf{iso}\ x \quad \equiv \quad x ; x^\smile = \mathsf{Id} \wedge x^\smile ; x = \mathsf{Id}$

$\mathsf{iso}\ x \quad \Rightarrow \quad (\exists g \bullet x ; g = \mathsf{Id} = g ; x)$

Division

Characterisation of $/$: $\quad a;b \sqsubseteq c \quad \equiv \quad a \sqsubseteq c/b$

Characterisation of $\backslash$: $\quad a;b \sqsubseteq c \quad \equiv \quad b \sqsubseteq a\backslash c$

Exact division:

$$(\exists z \bullet y = x;z) \equiv x;(x\backslash y) = y$$
$$(\exists z \bullet y = x\backslash z) \equiv x\backslash(x;y) = y$$

Shunting laws:

$\mathsf{univalent}\ f$	$\Rightarrow$	$(x;f \sqsubseteq y \Leftarrow x \sqsubseteq y;f^\smile)$
$\mathsf{total}\ f$	$\Rightarrow$	$(x;f \sqsubseteq y \Rightarrow x \sqsubseteq y;f^\smile)$
$\mathsf{mapping}\ f$	$\Rightarrow$	$(x;f \sqsubseteq y \equiv x \sqsubseteq y;f^\smile)$