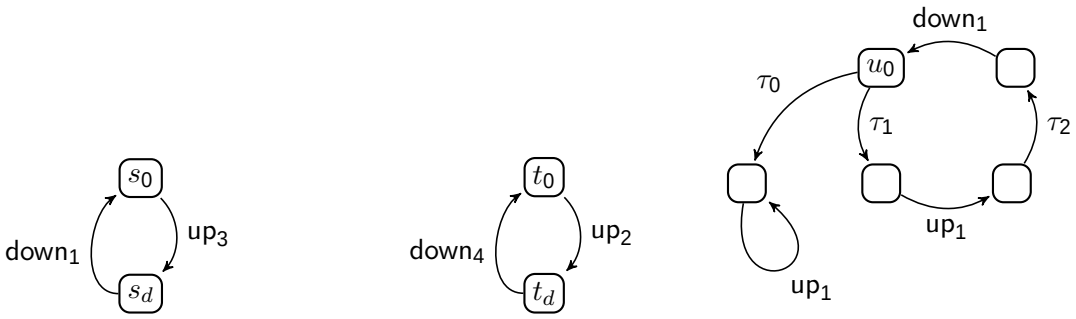

Figure 1: Nondeterministic machines

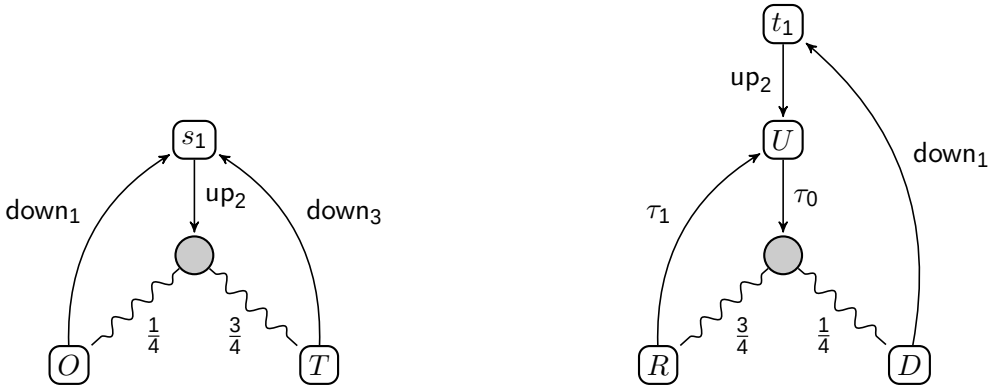

Figure 2: Probabilistic systems

up action, which accrues a bene t of 3 units, followed by a down action, which accrues a bene t of 1. The second machine performs the same actions but with bene ts 2 and 4 respectively. In some sense t_0 is an improvement on s_0; intuitively t_0 can simulate the behaviour of s_0 but in so doing accrue more bene ts; this is true even if one of its actions up is less bene cial than the corresponding action of s_0. The same is true for the machine u_0; it can also simulate the behaviour of s_0, with more bene t, although in this case some internal weighted actions, denoted by τ, participate in the simulation and add to the accumulation of bene ts. In our terminology we will write $s_0 \preccurlyeq_{sim} t_0$, $s_0 \preccurlyeq_{sim} u_0$. However we will have $t_0 \not\preccurlyeq_{sim} u_0$ because although u_0 can simulate the behaviour of t_0 it accumulates less bene t.

Similar informal reasoning can also be applied to probabilistic systems. Consider the systems in Figure 2. Here we have two kinds of nodes; the rst as in Figure 1 representing states of the systems, and the second representing probability distributions. For example the rst system, from state s_1, can perform the up action with bene t 2 and a quarter of the time it ends up in a state in which down can be performed with bene t only 1. But for the remaining three-quarters it ends up in a state in which down can be performed for the larger bene t 3. The circular darkened node

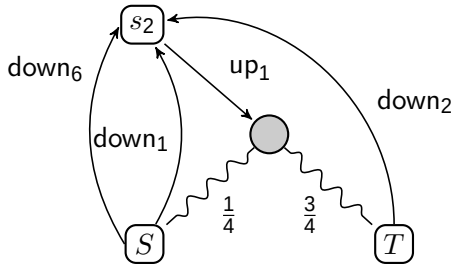

Figure 3: Nondeterministic and probabilistic systems

represents a distribution of states, with its outgoing edges describing the associated probabilities. Again intuitively we can see that s_1 is an improvement on s_0 because it can simulate s_0 and on average accrue slightly more bene ts; in our theory we will have $s_0 \; v_{sim} \; s_1$.

The mixture of probabilistic behaviour and internal actions introduces complications. Consider the system t_1 in Figure 2 which after performing an up action probabilistically decides internally whether to perform a down action for bene t 1, or branch back to make another probabilistic choice. However each time it reverts back it accumulates a non-zero bene t via the internal weighted action τ_1, albeit with diminishing probability. Nevertheless it will turn out that for our de nition of simulation $s_0 \; v_{sim} \; t_1$ and indeed $s_1 \; v_{sim} \; t_1$.

Systems exhibiting both probabilistic and nondeterministic behaviour require more complicated analysis. Consider the system in Figure 3. After performing the action up it nds itself either in a state in which the action down will accrue the bene t 2, or 25% of the time there will be a nondeterministic choice between it accruing either 1 or 6. In the literature there are numerous mechanisms, such as policies, schedulers, adversaries, etc. [Put94, Seg95, RKNP04] for resolving such choices. Here one can see if this choice systematically leads to the lower bene t 1 then s_2 will not simulate s_0 as it does not accrue su cient bene ts. This is a pessimistic outlook; an optimistic outlook means that the best choices are systematically made. If this is assumed then we will have $s_0 \; v_{sim} \; s_2$; in s_2 one execution of up followed by down will yield on average the bene t $1 + (\frac{3}{4} \;\; 2 + \frac{1}{4} \;\; 6) = 4$.

The main contribution of the paper is a coinductively de ned behavioural preorder v_{sim} between MDPs based on simulations which validate the examples discussed informally above. We con ne our attention to the optimistic approach to the resolution of nondeterministic choices, although as future work we hope to investigate the pessimistic approach. We also show that this preorder is compositional in the sense that it is preserved by structural operators for constructing MDPs from components. The main operator is one for composing two MDPs in parallel. In $P \; j \; Q$ the two MPDs P and Q remain independent, execute in parallel and may communicate by synchronising on complementary actions; these internal synchronisations accrue the combined bene ts of the associated complementary actions.

For nitary convergent MDPs, which are nite-state and nitely branching systems without divergence, we also provide two characterisations for the behavioural preorder v_{sim}. The rst is in terms of a *quantitative probabilistic logic L*. In addition to the standard logical connectives

such as conjunction and maximal fixed point this contains a novel quantitative *possibility* modality $\langle\alpha\rangle_w(\phi_1 \, p \, \phi_2)$, where p is some probability between 0 and 1. Intuitively this is satisfied by an MDP which can accrue at least the benefit w by performing the action α, and subsequently satisfy the probabilistic assertion $\phi_1 \, p \, \phi_2$. It turns out that the simulation preorder is completely determined by the logic L. Further evidence of the compatibility between the logic and the simulation relation is the fact that every system P has a *characteristic formula* $\phi(P)$ in the logic which captures its behaviour; informally system Q can simulate P if and only if it satisfies the characteristic formula $\phi(P)$.

Our second characterisation is in terms of a novel form of testing called *benefits* testing. Intuitively a system P can be tested by running it in parallel with another testing system T, and seeing the possible accrued benefits. In the presence of nondeterminism the execution of the combined system $(T \mid P)$ will result in a non-empty set of benefits, $\mathbf{Benefits}(T \mid P)$. Then systems P and Q can be compared by comparing the associated benefit sets $\mathbf{Benefits}(T \mid P)$ and $\mathbf{Benefits}(T \mid Q)$ where T ranges over some collection of possible tests. We show that the simulation preorder $\preceq_{sim}$ is also determined in this manner by a suitable collection of tests T.

The rest of this paper is organised as follows. Section 2 is devoted to an exposition of our model, which we call *weighted Markov Decision Processes*, *wMDPs*. These correspond to the diagrams we have been using informally in this introduction. The actions in a wMPD take the form $s \xrightarrow{\alpha}_w \mu$, where α is the label of the action, w its weight, or benefit, and μ a probability distribution which determines the next state. Following [Seg95, Seg96, DvGHM09], we make extensive use of the generalisation of this next-step relation to actions from distributions to distributions, $\Theta \xrightarrow{\alpha} \Omega$. Furthermore we are interested in *weak* theories, in which internal activity is not directly observable. So we generalise these actions to weak actions, of the form $s \Rightarrow^{\alpha}_w \mu$ and $\Theta \Rightarrow^{\alpha} \Omega$ respectively, actions in which occurrences of internal actions, denoted by τ, may occur an arbitrary number of times both before and after α. As have already been pointed out by many authors, [LSV07, DvGHM09], in a probabilistic setting we need to allow a potentially infinite number of internal actions to occur, *in the limit*. We follow the formalisation of this idea suggested in [DvGHM09] based on (weighted) hyper-derivations. We outline properties of these hyper-derivations but their proofs, being quite technical, are relegated to an appendix. One particularly significant property is that the set of weak derivatives from a given state, although in general uncountable, in a finite-state wMDP can be generated as the convex-closure of a finite number of derivatives. This is explained in Section 2.4. The proof is very complex, relying on notions such as static policies and payoffs [DvGHM09]. Consequently, again the details are relegated to an appendix.

Then, still in Section 2, we turn our attention to a subclass of wMDPs, called *bounded wMDPs*. In an arbitrary wMDP if $s \Rightarrow^{\tau}_w \mu$ then w may in general be infinite because of an indefinite accumulation of weights during an infinite internal computation. In bounded wMDPs we are guaranteed that such w's will always be a finite real number. Such wMDPs are the main focus of the paper, and their properties are studied in Section 2.5.

Section 3 is devoted to our notion of simulation, called *amortised weighted simulation*, based on ideas from [KAK05]. In the first subsection we give the definition and some examples. The formal simulation preorder $\preceq$ is defined coinductively but in Section 3.2 we show that in bounded wMDPs it can also be defined as the intersection of an infinite sequence of inductively defined relations. This result depends on compactness arguments, which we are able to employ in bounded wMDPs because of the finite generability property alluded to above. Then in Section 3.3 we show that the

simulation preorder can be captured by a very simple modal logic, again if we restrict attention to bounded wMDPs. This logic is quantitative in the sense that satisfying formulae depends to some extent on the bene ts which a process can accrue. The logical characterisation in turn depends on the approximation result from Section 3.2.

In Section 4 we o er another justi cation for our simulation based on testing [NH84]. Because of the presence of weights or bene ts in wMDPs we are able to use a novel form of (may) testing in which bene ts are accrued as tests are applied to processes; then processes can be compared in terms of their ability to accumulate bene ts. In section 4.1 this idea, *bene ts testing*, is explained in detail and we also show that it is preserved by the simulation preorder. More interesting is the result, for bounded wMDPs, that the preorder is completely determined by these tests. This proof requires a digression, in Section 4.2, into a more standard testing framework. Here we extend the ideas on [Seg96, DvGMZ07] by developing a version of multi-success testing suitable for wMDPs. In a non-trivial theorem we show that in bounded wMDPs both testing preorders, bene t-based and multi-success, coincide. The interest in multi-success testing is that we can mimic the results in [DvGHM09] to show that this form of testing can be captured by the modal logic of the previous section. Since we already know that the modal logic determines the simulation preorder we have therefore also established the soundness and completeness of bene ts testing for the simulation preorder.

Section 4 ends with a short discussion of another natural form of testing, *expected bene ts testing*, in which the average weight of each path of a computation leading to a success is associated with a test. By means of a simple example we show that the simulation preorder is not sound for this form of testing.

2 Weighted Markov decision processes

2.1 Introduction

There is considerable variation in the literature in the formal de nition of a (labelled) Markov decision process [RKNP04, Put94]. For the purpose of this paper we use De nition 2.1.

We rst x some notation. A (discrete) probability *subdistribution* over a set S is a function $\mu : S \to [0,1]$ with $\sum_{s \in S} \mu(s) \leq 1$; the *support* of such a μ is $\lceil \mu \rceil := \{ s \in S \mid \mu(s) > 0 \}$, and its *mass* $|\mu|$ is $\sum_{s \in \lceil \mu \rceil} \mu(s)$. A subdistribution is a (total, or full) *distribution* if $|\mu| = 1$. The point distribution $\overline{s}$ assigns probability 1 to s and 0 to all other elements of S, so that $\lceil \overline{s} \rceil = \{s\}$. With $D_{sub}(S)$ we denote the set of subdistributions over S, and with $D(S)$ its subset of full distributions. For $\mu, \nu \in D_{sub}(S)$ we write $\mu \leq \nu$ if $\mu(s) \leq \nu(s)$ for all $s \in S$.

Let $\{ \mu_k \mid k \in K \}$ be a set of subdistributions, possibly in nite. Then $\sum_{k \in K} \mu_k$ is the real-valued function in $S \to \mathbb{R}$ de ned by $(\sum_{k \in K} \mu_k)(s) := \sum_{k \in K} \mu_k(s)$. This is a partial operation on subdistributions because for some state s the sum of $\mu_k(s)$ might exceed 1. If the index set is nite, say $\{1..n\}$, we often write $\mu_1 + \ldots + \mu_n$. For p a real number from $[0,1]$ we use $p \cdot \mu$ to denote the subdistribution given by $(p \cdot \mu)(s) := p \cdot \mu(s)$. Finally we use ε to denote the everywhere-zero subdistribution that thus has empty support. These operations on subdistributions do not readily adapt themselves to distributions; yet if $\sum_{k \in K} p_k = 1$ for some collection of $p_k \geq 0$, and the μ_k are distributions, then so is $\sum_{k \in K} p_k \cdot \mu_k$. In general when $0 \leq p \leq 1$ we write $\mu \, {}_p\!\oplus \, \nu$ for $p \cdot \mu + (1-p) \cdot \nu$ where that makes sense, so that for example $\mu_1 \, {}_p\!\oplus \, \mu_2$ is always de ned, and is full if μ_1 and μ_2

are.

For $\Delta \in D_{sub}(S)$ and f a function with domain S, we write $\mathrm{Exp}_\Delta(f)$, the *expected value* of f over $\Delta \in D_{sub}(S)$, for $\sum_{s \in dom(\Delta)} \Delta(s) \cdot f(s)$. More generally suppose $f : S^k \to T$. This is lifted to a function $f^\dagger : D_{sub}(S)^k \to D_{sub}(T)$ by letting $f^\dagger(\Delta_1, \ldots, \Delta_n)(t) = \sum_{t=f(s_1,\ldots,s_k)} \Delta_1(s_1) \cdot \ldots \cdot \Delta_k(s_k)$. We will often abbreviate the lifted function $f^\dagger$ to simply f.

Definition 2.1 [Weighted Markov decision process] A *weighted Markov decision process* or wMDP is a 4-tuple $\langle S, \mathrm{Act}, W, \to \rangle$ where S is a set of states, Act a set of actions, W a set of weights, and $\to \subseteq S \times \mathrm{Act} \times W \times D(S)$. We normally write $s \xrightarrow{\alpha}_w \Delta$ to mean $(s, \alpha, w, \Delta) \in \to$.

In this paper we set W to be $\mathbb{R}_{\geq 0}$, the set of non-negative real numbers, and we assume Act has the structure $\mathrm{Act}_\tau = \mathrm{Act} \cup \{\tau\}$ where each a in Act has an inverse $\overline{a}$ satisfying $\overline{\overline{a}} = a$. We write $s \not\xrightarrow{\alpha}$ if there is no w, Δ such that $s \xrightarrow{\alpha}_w \Delta$. We also use the following terminology. A wMDP is

finite-state if S is a finite set;

finitely branching if for each $s \in S$, the set $\{(\alpha, w, \Delta) \mid s \xrightarrow{\alpha}_w \Delta\}$ is finite;

finitary if it is both finite-state and finitely branching,

deterministic if from every $s \in S$ there is at most one outgoing transition.

In the Introduction we have used a straightforward graphical representation for wMDPs; a state s is represented by a node $\boxed{s}$ while darkened circular nodes are used for distributions, and arrows between nodes and distributions are annotated with their weights. Often a point distribution is represented by the unique state in its support; see the first series of examples with initial states s_0, t_0 and u_0.

The simplest approach to discussing compositionality is, as in [Her02], to introduce a process calculus-like syntax for wMDPs. Our calculus, called CCMDP, is based on CCS:

$$P ::= \alpha_w.(\textstyle\sum_{i \in I} p_i \cdot P_i) \mid P \mid P \mid P + P \mid \mathbf{0} \mid P \backslash a \mid A \qquad (1)$$

The main operator is prefixing, $\alpha_w.(\sum_{i \in I} p_i \cdot P_i)$. Here α is taken from Act_τ, w from $\mathbb{R}_{\geq 0}$, I is a finite index set and p_i are probabilities satisfying $\sum_{i \in I} p_i = 1$. We also assume a set of definitional constants, ranged over by A, and we assume that each such A has a definition associated with it, a process term P_A. We often write these definitions as

$$A \stackrel{\text{def}}{=} P_A$$

We will use the auxiliary operator $\|$, letting $P \| Q$ stand for the process $(P \mid Q) \backslash \mathrm{Act}$.

Let $\mathcal{P}$ denote the set of all terms P definable in this language. Intuitively, we view each such term as describing a wMDP. Formally we describe one overarching wMDP where the states are all terms in $\mathcal{P}$ and the weighted actions $P \xrightarrow{\alpha}_w \Delta$ are those which can be derived by the rules in Figure 4; obvious symmetric counterparts to the rules (l-alt) (l-par) are omitted. In rule (l-act) we use the obvious notation $Dist(\{(p_i, P_i) \mid i \in I\})$ for constructing a distribution from the formal term $\sum_{i \in I} p_i \cdot P_i$. In rules (l-comm) and (l-par) we take advantage of the fact that

(l-act)

$$\alpha_w.(\ _{i2I}p_i\ \ P_i)\ \ ^{\alpha}!\ _w\ Dist(f\,(p_i, P_i)\ j\ i\ 2\ I\,g)$$

(l-alt)

$$\frac{P_1\ \ ^{\alpha}!\ _w}{P_1 + P_2\ \ ^{\alpha}!\ _w}$$

(l-par)

$$\frac{P_1\ \ ^{\alpha}!\ _w}{P_1\ j\ P_2\ \ ^{\alpha}!\ _w\ \ \ j\ P_2}$$

(l-comm)

$$\frac{P_1\ \ ^{a}!\ _{w_1}\ \ _1,\ \ P_2\ \ ^{\bar{a}}!\ _{w_2}\ \ _2}{P_1\ j\ P_2\ \ ^{\tau}!\ _w\ \ _1\ j\ \ _2}\quad w = w_1 + w_2$$

(l-hide)

$$\frac{P\ \ ^{\alpha}!\ _w}{Pna\ \ ^{\alpha}!\ _w\ \ na}\quad 6 = a; \bar{a}$$

(l-def)

$$\frac{P_A\ \ ^{\alpha}!\ _w}{A\ \ ^{\alpha}!\ _w}\quad A\ (\ P_A$$

Figure 4: Weighted actions

parallel composition can be viewed as a binary operator over process terms j: $P\ \ \ P\ \ !\ \ P$, and therefore can be lifted to distributions of processes as explained above: j^y: $P\ \ \ P\ \ !\ \ P$. An equivalent de nition is given by

$$(\ _1\ j^y\ \ _2)(Q) = \begin{cases} \ _1(P_1)\ \ \ _2(P_2) & \text{if } Q = P_1\ j\ P_2, \\ 0 & \text{otherwise} \end{cases}$$

and in the sequel we drop the annotation ^{y}. The hiding operator is treated in a similar manner.

Note that all of the wMDPs described graphically in the Introduction can be described in CCMDP. In the sequel we will not distinguish between the syntactic term P, its interpretation as a state in the wMDP de ned in Figure 4, and the wMDP it induces by considering only those states, that is process terms, accessible from it.

2.2 Lifted relations

In a wMDP actions are only performed by states, in that actions are given by relations from states to distributions. But formal systems or processes in general correspond to distributions over states, so in order to de ne what it means for a process to perform an action, we need to *lift* these relations so that they also apply to distributions. In fact we will nd it convenient to lift them to subdistributions.

We first recall some standard terminology. For any subset X of $\mathsf{R}\ D_{sub}(S)$, with S a set, let $\mathcal{I}X$, the *convex closure* of X, be the least set satisfying $\langle r,\ i \in \mathcal{I}X$ if and only if $\langle r,\ i = \sum_{i\in I} p_i\ \langle r_i,\ _i i$, where $\langle r_i,\ _i i \in X$ and $p_i \in [0,1]$, for some index set I such that $\sum_{i\in I} p_i = 1$. We say a set X is *convex* if $\mathcal{I}X = X$. Let R be a relation in $Y\ (\mathsf{R}_0\ D_{sub}(S))$. It is

1. *convex* whenever the set $\{\langle r,\ i \mid y\ R\ \langle r,\ i\}$ is convex for every y in Y; $\mathcal{I}R$ denotes the smallest convex relation containing R
2. *linear* whenever $_i\ R\ \langle r_i,\ _i i$ for $i \in I$ implies $(\sum_{i\in I} p_i\ _i)\ R\ (\sum_{i\in I} p_i\ \langle r_i,\ _i i)$ for any $p_i \in [0,1]$ $(i \in I)$ with $\sum_{i\in I} p_i \leq 1$
3. *decomposable* whenever $(\sum_{i\in I} p_i\ _i)\ R\ \langle w,\ i$ implies $\langle w,\ i = \sum_{i\in I} p_i\ \langle w_i,\ _i i$ for some weights w_i and subdistributions $_i$ such that $_i\ R\ \langle w_i,\ _i i$ for $i \in I$.

Note that if R is linear it is automatically convex.

Definition 2.2 Let $R\ S\ (\mathsf{R}_0\ D_{sub}(S))$ be a relation from states to pairs of weights and subdistributions. Then $\overline{R}\ D_{sub}(S)\ (\mathsf{R}_0\ D_{sub}(S))$ is the smallest linear relation that satisfies $s\ R\ \langle r,\ i$ implies $\overline{s}\ \overline{R}\ \langle r,\ i$.

By construction $\overline{R}$ is both linear and convex. Moreover the lifting operation is monotonic, in that $R_1 \subseteq R_2$ implies $\overline{R_1} \subseteq \overline{R_2}$. Also, because $s \in (\mathcal{I}R)$ implies $\overline{s}\ \overline{R}$ we have $\overline{R} = \overline{\mathcal{I}R}$. Finally note that if R itself is convex, we have that $\overline{s}\ \overline{R}$ and $s\ R$ are equivalent.

An application of this notion is when the relation is $\xrightarrow{\alpha}$ for $\alpha \in \mathsf{Act}_\tau$; in that case we also write $\xrightarrow{\alpha}$ for $(\overline{\xrightarrow{\alpha}})$. Thus, as source of a relation $\xrightarrow{\alpha}$ we now also allow distributions, and even subdistributions.

Lemma 2.3 $\overline{R}\ \langle r,\ i$ if and only if

1. $\ = \sum_{i\in I} p_i\ \overline{s_i}$, where I is an index set and $\sum_{i\in I} p_i \leq 1$,
2. For each $i \in I$ there is a pair $\langle r_i,\ _i i$ such that $s_i\ R\ \langle r_i,\ _i i$,
3. $r = \sum_{i\in I} p_i r_i$ and $\ = \sum_{i\in I} p_i\ _i$.

Proof. Straightforward.

An important point here is that a single state can be split into several pieces: that is, the decomposition of $\ $ into $\sum_{i\in I} p_i\ \overline{s_i}$ is not unique.

The lifting operation has yet another characterisation, this time in terms of *choice functions*.

Definition 2.4 Let $R\ S\ (\mathsf{R}_0\ D_{sub}(S))$ be a relation. Then $f : S \to (\mathsf{R}_0\ D_{sub}(S))$ is a *choice function for* R, written $f \in \mathsf{Ch}(R)$, if $s\ R\ f(s)$ for every $s \in \mathsf{dom}(R)$.

Note that if f is a choice function of R then f behaves properly at each state s in the domain of R, but for each state s' outside the domain of R, the value $f(s')$ can be arbitrarily chosen.

Proposition 2.5 Suppose $R\ S\ (\mathsf{R}_0\ D_{sub}(S))$ is a convex relation. Then for any $\in D_{sub}(S)$, $\overline{R}\ \langle w,\ i$ if and only if there is some choice function $f \in \mathsf{Ch}(R)$ such that $\langle w,\ i = \mathsf{Exp}\ (f)$.

Proof. First suppose $\langle w, \mu \rangle = \mathrm{Exp}(f)$ for some choice function $f \in \mathsf{Ch}(R)$, that is $\langle w, \mu \rangle = \sum_{s \in \mathrm{dom}(R)} \mu(s) \cdot f(s)$. It now follows from Lemma 2.3 that $\overline{R}\ \langle w, \mu \rangle$ since $s\ R\ f(s)$ for each $s \in \mathrm{dom}(R)$.

Conversely suppose $\overline{R}\ \langle w, \mu \rangle$; we have to find a choice function $f \in \mathsf{Ch}(R)$ such that $\langle w, \mu \rangle = \mathrm{Exp}(f)$. Applying Lemma 2.3 we know that

(i) $\mu = \sum_{i \in I} p_i \cdot \overline{s_i}$, for some index set I, with $\sum_{i \in I} p_i \leq 1$

(ii) $\langle w, \mu \rangle = \sum_{i \in I} p_i \cdot \langle w_i, \mu_i \rangle$ for some $\langle w_i, \mu_i \rangle$ satisfying $s_i\ R\ \langle w_i, \mu_i \rangle$.

Now define the function $f : S \to (R_0 \to D_{sub}(S))$ as follows:

if $s \in \mathrm{dom}(\mu)$ then $f(s) = \sum_{i \in I \mid s_i = s} (\frac{p_i}{\mu(s)}) \cdot \langle w_i, \mu_i \rangle$;

if $s \in \mathrm{dom}(R) \setminus \mathrm{dom}(\mu)$ then $f(s) = \langle w', \mu' \rangle$ for any $\langle w', \mu' \rangle$ with $s\ R\ \langle w', \mu' \rangle$;

otherwise, $f(s) = \langle 0, \varepsilon \rangle$, where ε is the empty subdistribution.

Note that if $s \in \mathrm{dom}(\mu)$ then $\mu(s) = \sum_{i \in I \mid s_i = s} p_i$ and therefore by convexity $s\ R\ f(s)$; so f is a choice function for R as $s\ R\ f(s)$ for each $s \in \mathrm{dom}(R)$. Moreover, a simple calculation shows that $\mathrm{Exp}(f) = \sum_{i \in I} p_i \cdot \langle w_i, \mu_i \rangle$, which by (ii) above is $\langle w, \mu \rangle$.

By Definition 2.2, a lifted relation is linear and convex; we now show that it is also decomposable.

Proposition 2.6 Let $R \subseteq D_{sub}(S) \times (R_0 \to D_{sub}(S))$ be a relation. Then $\overline{R}$ is decomposable.

Proof. Let $\overline{R}\ \langle w, \mu \rangle$ where $\mu = \sum_{i \in I} p_i \cdot \mu_i$. By Proposition 2.5, using that $\overline{R} = \overline{IR}$, there is a choice function $f \in \mathsf{Ch}(IR)$ such that $\langle w, \mu \rangle = \mathrm{Exp}(f)$. Take $\langle w_i, \mu_i \rangle := \mathrm{Exp}_i(f)$ for $i \in I$. Using that $\mathrm{dom}(\mu_i) \subseteq \mathrm{dom}(\mu)$, Proposition 2.5 yields $\mu_i\ \overline{R}\ \langle w_i, \mu_i \rangle$ for $i \in I$. Finally,

$$\sum_{i \in I} p_i \cdot \langle w_i, \mu_i \rangle = \sum_{i \in I} p_i \cdot \sum_{s \in \mathrm{dom}(\mu_i)} \mu_i(s) \cdot f(s) = \sum_{s \in \mathrm{dom}(\mu)} \sum_{i \in I} p_i \cdot \mu_i(s) \cdot f(s) = \sum_{s \in \mathrm{dom}(\mu)} \mu(s) \cdot f(s) = \mathrm{Exp}(f) = \langle w, \mu \rangle.$$

The converse to the above is not true in general: from $\overline{R}\ (\sum_{i \in I} p_i \cdot \langle w_i, \mu_i \rangle)$ it does not follow that μ can correspondingly be decomposed. For example, we have

$$\overline{a.(b_0.\mathbf{0} \oplus_{\frac{1}{2}} c_0.\mathbf{0})}\ \ {}^{a}\!\!\to_0 \tfrac{1}{2}\ \overline{b_0.\mathbf{0}} + \tfrac{1}{2}\ \overline{c_0.\mathbf{0}},$$

yet $\overline{a.(b_0.\mathbf{0} \oplus_{\frac{1}{2}} c_0.\mathbf{0})}$ cannot be written as $\frac{1}{2}\ \mu_1 + \frac{1}{2}\ \mu_2$ such that $\mu_1\ {}^{a}\!\!\to_0 \overline{b_0.\mathbf{0}}$ and $\mu_2\ {}^{a}\!\!\to_0 \overline{c_0.\mathbf{0}}$.

In fact a simplified form of Proposition 2.6 holds for un-lifted relations, provided they are convex:

Corollary 2.7 If $(\sum_{i \in I} p_i \cdot \overline{s_i})\ \overline{R}\ \langle w, \mu \rangle$ and R is convex, then $\langle w, \mu \rangle = \sum_{i \in I} p_i \cdot \langle w_i, \mu_i \rangle$ for weights w_i and subdistributions μ_i with $s_i\ R\ \langle w_i, \mu_i \rangle$ for $i \in I$.

Proof. Take μ_i to be $\overline{s_i}$ in Proposition 2.6, whence $\langle w, \mu \rangle = \sum_{i \in I} p_i \cdot \langle w_i, \mu_i \rangle$ for some weights w_i and subdistributions μ_i such that $\overline{s_i}\ \overline{R}\ \langle w_i, \mu_i \rangle$ for $i \in I$. Because R is convex, we then have $s_i\ R\ \langle w_i, \mu_i \rangle$.

2.3 Hyper-derivations

As we have seen in the Introduction, when reasoning informally that t_1 can simulate s_0, the limiting behaviour of internal computations must be taken into account. We formalise this by extending the approach originally given in [DvGHM09]. By employing the lifting operation de ned in Section 2.2, we now formally de ne weak actions performed by subdistributions.

De nition 2.8 [Hyper-derivations] A hyper-derivation consists of a collection of subdistributions $\ ,\ \overset{!}{k}\ ,\ \ _k$, for $k \quad 0$, with the following properties:

$$\begin{array}{rcl} = & \overset{!}{0} + & 0 \\ \overset{!}{0} \ \overset{\tau}{!}_{w_0} & \overset{!}{1} + & 1 \\ \vdots & & \\ \overset{!}{k} \ \overset{\tau}{!}_{w_k} & \overset{!}{k+1} + & k+1 \\ \vdots & & \\ \overset{\emptyset}{} = & \sum\limits_{k=0}^{\infty} & k \end{array} \tag{2}$$

Then we call $\overset{\emptyset}{} = \sum_{k=0}^{1} k$ a *hyper-derivative* of , and write $\overset{\tau}{)}_w \overset{\emptyset}{}$, where $w = \sum_{k=0}^{1} w_i$, to mean that can make a *(weak) hyper-move* to its derivative $\overset{\emptyset}{}$ with weight w. Note that in general $w \ 2$ R $_0 \ [\ f \ 1 \ g$; that is there is no guarantee that the sum $\sum_{k=0}^{1} w_i$ has a nite limit.

One question to answer is when can we ensure that this sum does indeed have a limit. This will be studied in Section 2.5.

Example 2.9 Consider the wMDP with initial state t_1 discussed in the Introduction. Then we have the following hyper-derivation:

$$\begin{array}{rcl} \overline{U} & = & \overline{U} + \varepsilon \\ \overline{U} & \overset{\tau}{!}_0 & \frac{3}{4}\ \overline{R} + \frac{1}{4}\ \overline{D} \\ \frac{3}{4}\ \overline{R} & \overset{\tau}{!}_{\frac{3}{4}} & \frac{3}{4}\ \overline{U} + \varepsilon \\ \frac{3}{4}\ \overline{U} & \overset{\tau}{!}_0 & (\frac{3}{4})^2\ \overline{R} + (\frac{3}{4})\frac{1}{4}\ \overline{D} \\ (\frac{3}{4})^2\ \overline{R} & \overset{\tau}{!}_{(\frac{3}{4})^2} & (\frac{3}{4})^2\ \overline{U} + \varepsilon \\ & \vdots & \\ (\frac{3}{4})^k\ \overline{U} & \overset{\tau}{!}_0 & (\frac{3}{4})^{(k+1)}\ \overline{R} + (\frac{3}{4})^k\frac{1}{4}\ \overline{D} \\ (\frac{3}{4})^{(k+1)}\ \overline{R} & \overset{\tau}{!}_{(\frac{3}{4})^{(k+1)}} & (\frac{3}{4})^{(k+1)}\ \overline{U} + \varepsilon \\ & \vdots & \end{array}$$

That is, $\overline{U} \Longrightarrow_\tau w \sum_{k=0}^{1} (\frac{3}{4})^k(\frac{1}{4}\ \overline{D})$ where $w = \sum_{k=1}^{1}(\frac{3}{4})^k$. However this weight evaluates to 3, while the sum of the subdistributions is the full point distribution $\overline{D}$. In other words $\overline{U} \Longrightarrow_\tau{}_3\ \overline{D}$.

Definition 2.10 [Weak actions] In a wMDP $\langle S, \mathsf{Act}_\tau, \mathsf{R}_{\geq 0}, \ldots \rangle$ for $\ldots, \ldots \in \mathcal{D}_{sub}(S)$ we write $\Longrightarrow_w$ whenever $\Longrightarrow_{w_1} \circ \xrightarrow{a}_{w_2} \circ \Longrightarrow_{w_3}$ and $w = w_1 + w_2 + w_3$.

We complete this subsection by enumerating some elementary properties of hyper-derivations; their proofs are relegated to Appendix A.

Proposition 2.11

1. If $\Longrightarrow_v$ then $\ldots \ldots$.
2. If $\Longrightarrow_v$ and $p \in \mathsf{R}_{\geq 0}$ such that $\ldots \leq 1$, then $\ldots \Longrightarrow_{pv} \ldots$.
3. (Binary decomposition) If $\ldots + \ldots \Longrightarrow_v \ldots$ then $\ldots = \ldots + \ldots$ with $\ldots \Longrightarrow_v \ldots$, $\ldots \Longrightarrow_v \ldots$, and $v = v + v$.
4. (Linearity) Let $p_i \in [0,1]$ for $i \in I$ where $\sum_{i \in I} p_i \leq 1$. Then $\ldots_i \Longrightarrow_{w_i} \ldots_i$ for all $i \in I$ implies $\sum_{i \in I} p_i \ldots_i \Longrightarrow_{(\sum_{i \in I} p_i w_i)} \sum_{i \in I} p_i \ldots_i$.
5. (Decomposability) suppose $\sum_{i \in I} p_i \ldots_i \Longrightarrow_w \ldots$, where $p_i \in [0,1]$ and $\sum_{i \in I} p_i \leq 1$. Then $w = \sum_{i \in I} p_i\ w_i$ and $\ldots = \sum_{i \in I} p_i \ldots_i$ for weights w_i and subdistributions $\ldots_i$ such that $\ldots_i \Longrightarrow_{w_i} \ldots_i$ for all $i \in I$.

Proof. See Appendix A.

With these results the relation $\Longrightarrow_\tau \in \mathcal{D}_{sub}(S) \times (\mathsf{R}_{\geq 0} \times \mathcal{D}_{sub}(S))$ can be obtained as the lifting of a relation $\Longrightarrow_S$ from S to $\mathsf{R}_{\geq 0} \times \mathcal{D}_{sub}(S)$, which is defined by writing $s \Longrightarrow_S \langle w, \ldots \rangle$ just when $\overline{s} \Longrightarrow_w \ldots$.

Corollary 2.12 $\overline{(\Longrightarrow_S)} = (\Longrightarrow_\tau)$.

Proof. That $\overline{(\Longrightarrow_S)}\ \langle w, \ldots \rangle$ implies $\Longrightarrow_w$ is a simple application of Part 4 followed by Part 3 of Proposition 2.11. For the other direction, suppose $\Longrightarrow_w \ldots$. Given that $\ldots = \sum_{s \in \mathsf{dom}(\ldots)} \ldots(s)\ \overline{s}$, Part 5 of the same proposition enables us to decompose $\ldots$ into $\sum_{s \in \mathsf{dom}(\ldots)} \ldots(s)\ \ldots_s$ and w into $\sum_{s \in \mathsf{dom}(\ldots)} \ldots(s)\ w_s$, where $\overline{s} \Longrightarrow_{w_s} \ldots_s$ for each s in $\mathsf{dom}(\ldots)$. But the latter actually means that $s \Longrightarrow_S \langle w_s, \ldots_s \rangle$, and so by definition this implies $\overline{(\Longrightarrow_S)}\ \langle w, \ldots \rangle$.

Corollary 2.12 implies that the hyper-derivation relation $\Longrightarrow_\tau$ is convex. It is trivial to check that $\Longrightarrow_\tau$ is also reflexive because $\Longrightarrow_0 \ldots$ for any $\ldots \in \mathcal{D}_{sub}(S)$. But transitivity is less obvious.

Theorem 2.13 [Transitivity of $\Longrightarrow_\tau$] If $\Longrightarrow_u \ldots$ and $\ldots \Longrightarrow_v \ldots$ then $\Longrightarrow_{u+v} \ldots$.

Proof. See Appendix A.

2.4 Finite generability

We aim to establish that, for any subdistribution in a nitary wMDP where hyper-derivations only yield nite weights, the set $\{\langle w, \delta'\rangle \mid \delta \stackrel{\tau}{\Rightarrow}_w \delta'\}$ can be generated by taking the convex closure of a nite set of pairs $\{\langle w_1, \delta_1\rangle, \ldots, \langle w_n, \delta_n\rangle\}$. The proof is non-trivial and requires a digression into the world of payo functions and policies.

Let us x a nite-state space $S = \{s_1, \ldots, s_n\}$ with n 1 and de ne an extended state space $S + \{s_0\}$. This allows us to deal with vectors and in particular to use vector arithmetic. For example, a subdistribution 2 $D_{sub}(S)$ can be viewed as the n-dimensional vector $\langle (s_1), \ldots, (s_n)\rangle$, and a pair $\langle w, \rangle$ consisted of weight w and subdistribution may be viewed as the $(n+1)$-dimensional vector $\langle w, (s_1), \ldots, (s_n)\rangle$ in some contexts.

De nition 2.14 [Weight functions] A *weight function* is a function $\mathsf{w} : S + \{s_0\} \to [-1, 1]$ from the extended state space into the real interval [-1,1].

This notion of *weight function* is not to be confused with the weights associated with actions in a wMDP; instead they will be applied to the results of executing hyper-derivations. We often consider a weight function as the $(n+1)$-dimensional vector $\langle \mathsf{w}(s_0), \ldots, \mathsf{w}(s_n)\rangle$. Therefore the the result of applying the weight function w to $\langle w, \rangle$ is given by the inner product of the two vectors $\mathsf{w}\ \langle w, \rangle$.

De nition 2.15 [Payo functions] Given a weight function w, the *payo function* $\mathsf{P}^{\mathsf{w}}_{\max} : S \to \mathbb{R}$ is de ned by

$$\mathsf{P}^{\mathsf{w}}_{\max}(s) = \sup\{\mathsf{w}\ \langle w, \delta'\rangle \mid \delta \stackrel{\tau}{\Rightarrow}_w \delta'\}$$

and we will generalise it to be of type $D_{sub}(S) \to \mathbb{R}$ by letting $\mathsf{P}^{\mathsf{w}}_{\max}( ) = \sum_{s \in d\ e} (s)\ \mathsf{P}^{\mathsf{w}}_{\max}(s)$.

A priori these payo functions for a given state s are determined by its set of hyper-derivatives. However they can also be calculated by using derivative policies, decision mechanisms for guiding a computation through a wMDP.

De nition 2.16 A *static (derivative) policy* (SP) for a wMDP is a partial function $\mathsf{pp} : S \rightharpoonup \mathbb{R}_{>0} \times D(S)$ such that if $\mathsf{pp}(s) = \langle w, \rangle$ then $s \stackrel{\tau}{\to}_w$.

If pp is unde ned at s, we write $\mathsf{pp}(s)$ ". Otherwise, we write $\mathsf{pp}(s)$#.

A derivative policy pp, as its name suggests, can be used to guide the derivation of a weak derivative. Suppose $\overline{s} \stackrel{\tau}{\Rightarrow}_w$, using a derivation as given in De nition 2.8; for convenience we abbreviate $(\ \stackrel{!}{k} + \ k)$ to $\ k$. Then we write $\overline{s} \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w}$ whenever $\ 0 = \overline{s}$ and, for all k 0,

(a) $\langle w_{k+1}, \ k+1\rangle = \sum \{\ k(s)\ \mathsf{pp}(s) \mid s \in d\ k e \text{ and } \mathsf{pp}(s)\#\}$

(b) $\ k(s) = \begin{cases} 0 & \text{if } \mathsf{pp}(s)\# \\ k(s) & \text{otherwise} \end{cases}$

We refer to $\overline{s} \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w}$ as a hyper-SP-derivation from s. Intuitively the conditions mean that the derivation of from s, and the accumulation of weights, is guided at each stage by the policy pp; the division of $\ k$ into $\stackrel{!}{k}$, the subdistribution which will continue marching, and $\ k$, the subdistribution which will stop, is determined by the domain of the derivative policy pp.

Lemma 2.17 Let pp be derivative policy in a pLTS. Then

(1) If $\bar{s} =^{\tau})_{\mathrm{pp},v}$ and $\bar{s} =^{\tau})_{\mathrm{pp},w}$ then $v = w$ and = .

(2) For every state s there exists some $w,$ such that $\bar{s} =^{\tau})_{\mathrm{pp},w}$.

Proof. To prove part (1) consider the derivation of $\bar{s} =^{\tau})_{v}$ and $\bar{s} =^{\tau})_{w}$ as in De nition 2.8, via the subdistributions $_k,$ $_k^{!},$ $_k$ and $_k,$ $_k^{!},$ $_k$ respectively, and the weights v_k, w_k. Because both derivations are guided by the same derivative policy pp it is easy to show by induction on k that

$$_k = \quad _k \qquad _k^{!} = \quad _k^{!} \qquad _k = \quad _k \qquad v_k = w_k$$

from which = and $v = w$ follow immediately.

To prove (2) generate subdistributions $_k,$ $_k^{!},$ $_k$ and weights w_k for each k 0 satisfying the constraints of De nition 2.8 by applying (a) and (b) above to pp. The result will then follow by letting be $\mathrm{P}_{k\ 0}\ _k$ and w to be $\mathrm{P}_{k\ 0}\, w_k$.

The net e ect of this lemma is that a derivative policy pp determines a *total* function over states. Moreover a policy can used as an alternative to the method used in De nition 2.15 to calculate weighted payo s.

De nition 2.18 [Policy-following payo s] Given a weight function w, and static policy pp, the *policy-following payo function* $\mathrm{P}^{\mathrm{pp},\mathbf{w}} : S\ !\ \mathrm{R}^{1}$ is de ned by

$$\mathrm{P}^{\mathrm{pp},\mathbf{w}}(s) = \mathrm{w}\ \hbar w,\ ^{0}\, i$$

where $w,$ are determined uniquely by $\bar{s} =^{\tau})_{\mathrm{pp},w}\ ^{0}$.

It should be clear that the use of derivative policies limits considerably the scope for calculating weighted payo s. Each particular policy can only derive one weak derivative, and moreover in nitary pLTS there are only a nite number of derivative policies. Nevertheless this limitation is more apparent than real.

Theorem 2.19 In a nitary wMDP, for any weight function w there exists a static policy pp such that $\mathrm{P}^{\mathbf{w}}_{\max} = \mathrm{P}^{\mathrm{pp},\mathbf{w}}$.

The proof of this theorem is non-trivial, requiring the use of discounted policies and payo s. It is relegated to Appendix B.

Theorem 2.20 [Finite generability] Let $\mathrm{pp}_1, ..., \mathrm{pp}_n$ $(n$ 1) be all the static policies in a nitary wMDP. Suppose $=^{\tau})_{\mathrm{pp}_i,w_i}\ ^{0}_{i}$ and $w_i < 1$ for all 1 i n. If $\mathrm{P}\ =^{\tau})_{w}\ ^{0}$ then there are probabilities p_i for all 1 i n with $\mathrm{P}_{i=1}^{n} p_i = 1$ such that $\hbar w,\ ^{0}\, i = \mathrm{P}_{i=1}^{n} p_i\ \hbar w_i,\ ^{0}_{i}\, i$.

Proof. Let X be the convex closure of the nite set $f\hbar w_i,\ ^{0}_{i}\, i\, j\, 1$ i ng. It su ces to show that whenever $=^{\tau})_{w}\ ^{0}$ then $\hbar w,\ ^{0}\, i$ belongs to X. Suppose for a contradiction that $\hbar w,\ ^{0}\, i$ is not in X. Since X is convex, Cauchy closed and bounded, by the Hyperplane separation theorem, Theorem 1.2.4 in [Mat02], $\hbar w,\ ^{0}\, i$ can be separated from X by a hyperplane H whose normal can

be scaled into $[-1,1]$ because we are in finitely many dimensions. The scaled normal induces a weight function $\mathbf{w}_H$ such that, for some $c \in \mathbb{R}$, we have $\mathbf{w}_H(\langle w, \pi \rangle) > c$ but $\mathbf{w}_H(x) < c$ for all $x \in X$. Then we have $P^{\mathbf{w}_H}_{\max}(\quad) > c$ but $P^{pp_i, \mathbf{w}_H}(\quad) < c$ for all $0 \quad i \quad n$, contradicting Theorem 2.19. Therefore, $\langle w, \pi \rangle$ must be in X, and is a convex combination of $\{\langle w_i, \pi_i \rangle \mid 1 \quad i \quad n\}$.

Remark 2.21 It is important that in Theorem 2.20 the weight given by every static policy is finite. Consider a wMDP consisted of two states s_1, s_2 and two transitions $s_1 \xrightarrow{\tau} \overline{s_2}$, $s_1 \xrightarrow{\tau} \overline{s_1}$. It can only have two static policies. The first one, say pp_1, is given by $pp_1(s_1) = \langle 1, \overline{s_2} \rangle$ and $pp_1(s_2)$ ". The second one, say pp_2 is given by $pp_2(s_1) = \langle 1, \overline{s_1} \rangle$ and $pp_2(s_2)$ ". They determine two hyper-derivations from s_1, namely $\overline{s_1} \Rightarrow_{pp_1,1} \overline{s_2}$ and $\overline{s_1} \Rightarrow_{pp_2,1} \varepsilon$. Now consider the hyper-derivation $\overline{s_1} \Rightarrow_2 \overline{s_1}$. Clearly, $\langle 2, \overline{s_1} \rangle$ is not a convex combination of $\langle 1, \overline{s_2} \rangle$ and $\langle 1, \varepsilon \rangle$.

Here the culprit is pp_2 which gives an infinite weight. In fact, the convex closure of the set $\{\langle 1, \overline{s_2} \rangle, \langle 1, \varepsilon \rangle\}$ is unbounded, thus the Hyperplane separation theorem does not apply, and as a matter of fact it is impossible to separate $\langle 2, \overline{s_1} \rangle$ from that set.

2.5 Bounded wMDPs

Definition 2.22 A *bounded wMDP* is a finitary wMDP such that if $\quad$ is a subdistribution over it and

$$\xrightarrow{\tau}_{w_1} \quad 1 \quad \xrightarrow{\tau}_{w_2} \quad 2 \quad \xrightarrow{\tau}_{w_3}$$

then $\sum_{i=1}^{1} w_i < 1$.

In other words, a bounded wMDP is a finitary wMDP that might diverge, but with bounded weights.

In this section we give an alternative characterisation of boundedness (Theorem 2.27), followed by a useful criteria which ensures boundedness (Theorem 2.29).

Definition 2.23 A wMDP is *convergent* if no state is wholly divergent, i.e. $\overline{s} \Rightarrow_w \varepsilon$ for no state $s \in S$ and weight w.

We will show that this condition is sufficient to ensure that a finitary wMDP is bounded.

Lemma 2.24 Let $\quad$ be a subdistribution in a *finite-state, convergent* and *deterministic* wMDP. If $\Rightarrow_w$ then

1. w is a finite real number and
2. $| \quad | = | \quad |$.

Proof. Since the wMDP is convergent, then $\overline{s} \Rightarrow_w \varepsilon$ for no state $s \in S$ and weight w. In other words, each τ sequence from a state s is finite and ends with a distribution $\quad_{n_s}$ which cannot enable a τ transition.

$$\overline{s} \xrightarrow{\tau}_{w_1} \quad 1 \quad \xrightarrow{\tau}_{w_2} \quad 2 \quad \xrightarrow{\tau}_{w_3} \qquad \xrightarrow{\tau}_{w_{n_s}} \quad n_s \quad 9$$

In a deterministic wMDP, each state has at most one outgoing transition. So from each s there is a unique τ sequence with length n_s 0. Let p_s be $_{n_s}(s^0)$ where s^0 is any state in the support of $_{n_s}$. We set

$$\begin{aligned} n &= \max f n_s \, j \, s \; 2 \; Sg \\ p &= \min f p_s \, j \, s \; 2 \; Sg \end{aligned}$$

Note that since we are considering a nite-state wMDP both n and p are well de ned. Now let $=^{\tau})_w$ ^{0} be any hyper-derivation constructed by a collection of $_k^!$, $_k$, w_k such that

$$\begin{aligned} &= \quad {}_0^! + \quad {}_0 \\ {}_0^! \quad {}^{\tau}!_{w_0} \quad & {}_1^! + \quad {}_1 \\ &\vdots \\ {}_k^! \quad {}^{\tau}!_{w_k} \quad & {}_{k+1}^! + \quad {}_{k+1} \\ &\vdots \end{aligned}$$

with $w = \mathsf{P}_{k=0}^{1} w_k$ and $^0 = \mathsf{P}_{k=0}^{1} \; {}_k$. From each $_{kn+i}^!$ with k, i 2 N, the block of n steps of τ transition leads to $_{(k+1)n+i}^!$ such that $j \; {}_{(k+1)n+i}^! j \quad j \; {}_{kn+i}^! j(1 \quad p)$. It follows that

$$\begin{aligned} \mathsf{P}_{j=0}^{1} j \; {}_j^! j &= \mathsf{P}_{i=0}^{n \; 1} \mathsf{P}_{k=0}^{1} j \; {}_{kn+i}^! j \\ &\quad \mathsf{P}_{i=0}^{n \; 1} \mathsf{P}_{k=0}^{1} j \; {}_i^! j(1 \quad p)^k \\ &= \mathsf{P}_{i=0}^{n \; 1} j \; {}_i^! j \tfrac{1}{p} \\ &\quad j \; {}_0^! j \tfrac{n}{p} \end{aligned}$$

Since the wMDP is nite-state and deterministic, it is nitely branching. Therefore, there exists a maximum weight $w_{\max}$ such that whenever $s \; {}^{\tau}!_v$ then $v \quad w_{\max}$. It follows that

$$w = \sum_{i=0}^{\infty} w_i \quad \sum_{i=0}^{\infty} j \; {}_i^! j w_{\max} \quad \frac{j \; {}_0^! j n w_{\max}}{p}$$

which means that the weight w is nite.

From above, $\mathsf{P}_{j=0}^{1} j \; {}_j^! j$ is bounded (by $j \; {}_0^! j \frac{n}{p}$). It follows that $\lim_{k \, ! \, 1} \; {}_k^! = 0$, which in turn means that $j \; {}^0 j = j \quad j$.

Example 2.25 In Lemma 2.24 it is important to require the wMDP to be convergent. In a nite-state deterministic but divergent system, a hyper-derivation $=^{\tau})_w$ ^{0} may yield an in nite weight w, even in the case that both and ^{0} are full distributions. For example, consider a system consisting of one state s together with a self τ loop $s \; {}^{\tau}!_1 \bar{s}$. We construct a hyper-derivation as follows.

$$\begin{aligned} \bar{s} &= \tfrac{1}{2}\bar{s} + \tfrac{1}{2}\bar{s} \\ \tfrac{1}{2}\bar{s} \quad {}^{\tau}!_{\frac{1}{2}} \quad & \tfrac{1}{3}\bar{s} + (\tfrac{1}{2} \quad \tfrac{1}{3})\bar{s} \\ \tfrac{1}{3}\bar{s} \quad {}^{\tau}!_{\frac{1}{3}} \quad & \tfrac{1}{4}\bar{s} + (\tfrac{1}{3} \quad \tfrac{1}{4})\bar{s} \\ &\vdots \\ {}^0 &= \bar{s} \end{aligned}$$

So $\bar{s}$ makes a hyper-derivation to itself, but with weight $\mathsf{P}_{k=2}^{1} \frac{1}{k} = 1$.

Lemma 2.26 [Distillation of divergence - static case] In a nite-state wMDP if there is a hyper-SP-derivation $=^{\tau})_{\mathrm{pp},w}$ ^{0}, there exists subdistribution $^{0}_{\varepsilon}$ such that $=^{\tau})_{w_1}$ (^{0} + $^{0}_{\varepsilon}$), j j = j ^{0} + $^{0}_{\varepsilon}j$, $^{0}_{\varepsilon}$ $=^{\tau})_{w_2}$ ε, w_1 is nite and $w_1 + w_2 = w$.

Proof. (*Schema*) We modify pp so as to obtain a static policy pp^{0} by setting pp$^{0}(s)$ = pp(s) except when $\overline{s}$ $=^{\tau})_{\mathrm{pp},w_s}$ ε for some weight w_s, in which case we set pp$^{0}(s)$ ". Intuitively, for any state s which can potentially leads to total divergence under policy pp, the new policy pp^{0} requires it to stop marching at the very beginning. The new policy determines a unique hyper-SP-derivation $=^{\tau})_{\mathrm{pp}',w_1}$ ^{00} for some w_1 and ^{00}, and induces a sub-wMDP from the wMDP induced by pp. Note that the sub-wMDP is deterministic, and convergent too because all divergent states in the original wMDP do not contribute any τ move in the sub-wMDP. By Lemma 2.24, we know that w_1 is nite and j j = j ^{00}j. We split ^{00} up into $^{00}_{1}$ + $^{00}_{\varepsilon}$ so that each state in d $^{00}_{\varepsilon}e$ is wholly divergent under policy pp and $^{00}_{1}$ is supported by all other states. From $^{0}_{\varepsilon}$ the policy pp determines the hyper-SP-derivation $^{0}_{\varepsilon}$ $=^{\tau})_{\mathrm{pp},w_2}$ ε for some w_2. Combining the two hyper-SP-derivations we have $\overline{s}$ $=^{\tau})_{\mathrm{pp}',w_1}$ $^{00}_{1}$ + $^{00}_{\varepsilon}$ $=^{\tau})_{\mathrm{pp},w_2}$ $^{00}_{1}$.

In the above analysis, we divide the original hyper-SP-derivation into two stages by letting the subdistribution $^{00}_{\varepsilon}$ pause in the rst stage and then resume marching in the second stage. Note that the two-staged hyper-SP-derivation consists of the same τ transitions from the original hyper-SP-derivation, which means that the overall weight and the nal subdistribution remain the same as before, thus we have $w_1 + w_2 = w$ and $^{00}_{1}$ = ^{0}.

Theorem 2.27 A nitary wMDP is bounded if and only if for any subdistribution , $=^{\tau})_{w}$ ^{0} implies w is a nite real number.

Proof. (*(*) First consider a nitary wMDP where we are assured that for any hyper-derivation from any distribution $=^{\tau})_{w}$ ^{0}, the weight w is nite. It is straightforward to see that the wMDP is bounded: if $=^{\tau})_{w}$ ε, then by the hypothesis we know that w is nite.

(*)*) In a nitary wMDP, there are only nitely many static policies, say pp$_i$ for i *2* I where I is a nite index set. For each pp$_i$ we have the unique hyper-SP-derivation $=^{\tau})_{\mathrm{pp}_i,w_i}$ $^{0}_{i}$. By Lemma 2.26 there exists subdistribution $^{0}_{i\varepsilon}$ such that $=^{\tau})_{w_{i1}}$ ($^{0}_{i}$ + $^{0}_{i\varepsilon}$), j j = j $^{0}_{i}$ + $^{0}_{i\varepsilon}j$, $^{0}_{i\varepsilon}$ $=^{\tau})_{w_{i2}}$ ε, w_{i1} is nite and $w_{i1} + w_{i2} = w_i$. If the wMDP is bounded, then w_{i2} is nite. It follows that w_i is also nite as it is the sum of two nite real numbers. Now we can apply Theorem 2.20 to obtain that whenever $=^{\tau})_{w}$ ^{0} then w is a convex combination of fw_i j i *2* Ig which must be nite.

This theorem enables us to generalise Lemma 2.26 to arbitrary hyper-derivations, provided we restrict attention to bounded wMDPs.

Corollary 2.28 [Distillation of divergence - general case] In a bounded wMDP if $=^{\tau})_{w}$ ^{0} then there exists subdistribution $^{0}_{\varepsilon}$ such that $=^{\tau})_{w_1}$ (^{0} + $^{0}_{\varepsilon}$), j j = j ^{0} + $^{0}_{\varepsilon}j$, $^{0}_{\varepsilon}$ $=^{\tau})_{w_2}$ ε and $w_1 + w_2 = w$.

Proof. Let $f$pp$_i$ j i *2* Ig (I is a nite index set) be all the static policies in the bounded wMDP. Each policy determines a hyper-SP-derivation $=^{\tau})_{\mathrm{pp}_i,w_i}$ $^{0}_{i}$. By Theorem 2.27, we know that $w_i <$ *1* for all i *2* I. From Theorem 2.20 we know that if $=^{\tau})_{w}$ ^{0} then $hw,$ ^{0}i = $\mathrm{P}_{i2I}\, p_i$ $hw_i,$ $^{0}_{i}i$

for some p_i with $\sum_{i2I} p_i = 1$ and $\stackrel{\tau}{\Rightarrow}_w \stackrel{0}{i}$. By Lemma 2.26, for each $i \in I$, there is some $\stackrel{0}{i,\varepsilon}$ such that $\stackrel{\tau}{\Rightarrow}_{w_{i1}} (\stackrel{0}{i} + \stackrel{0}{i,\varepsilon})$, $\sum_{i2I} j \stackrel{0}{i} + \stackrel{0}{i,\varepsilon} j$, $\stackrel{0}{i,\varepsilon} \stackrel{\tau}{\Rightarrow}_{w_{i2}} \varepsilon$ and $w_{i1} + w_{i2} = w_i$. Let $w_1 = \sum_{i2I} p_i w_{i1}$, $w_2 = \sum_{i2I} p_i w_{i2}$, $\stackrel{0}{\varepsilon} = \sum_{i2I} p_i \stackrel{0}{i,\varepsilon}$. By Proposition 2.11(4), it can be seen that $\stackrel{\tau}{\Rightarrow}_{w_1} (\stackrel{0}{} + \stackrel{0}{\varepsilon})$, $j \ j = j \stackrel{0}{} + \stackrel{0}{\varepsilon} j$, $\stackrel{0}{\varepsilon} \stackrel{\tau}{\Rightarrow}_{w_2} \varepsilon$ and $w_1 + w_2 = w$.

Theorem 2.27 gives a useful property of bounded wMDPs, but there is a simpler criteria which ensures boundedness.

Theorem 2.29 Every *nitary* and *convergent* wMDP is also bounded.

Proof. In a nitary and convergent wMDP, suppose $\stackrel{\tau}{\Rightarrow}_w \stackrel{0}{}$. We show that the weight w is nite. Let $\mathrm{pp}_1, ..., \mathrm{pp}_n$ (n 1) be all the static policies in a nitary wMDP. Each static policy pp_i induces a deterministic sub-wMDP from the original wMDP, and determines a hyper-derivation $\stackrel{\tau}{\Rightarrow}_{\mathrm{pp}_i, w_i} \stackrel{0}{i}$ from . Clearly, the sub-wMDP is also convergent. By Lemma 2.24, we know that $w_i < 1$ and $j \ j = j \ _i j$ for each i. Suppose $\stackrel{\tau}{\Rightarrow}_w \stackrel{0}{}$. It follows from Theorem 2.20 that $h w, \stackrel{0}{} i$ is an interpolation of $h w_1, \stackrel{0}{1} i, ..., h w_n, \stackrel{0}{n} i$. Therefore, we have $j \ j = j \stackrel{0}{} j$ and $w < 1$.

The nal result of this section concerns closure with respect to parallel composition. This will be useful in Section 4, where we de ne a testing preorder between processes (De nition 4.10).

Theorem 2.30 If P is a bounded wMDP and Q is a nite wMDP, then their parallel composition $P \ j \ Q$ is bounded.

Proof. (*Schema*) We use the simple syntax to represent nite wMDPs.

$$Q \ := \ \mathbf{0} \ j \ \sum_{i2I} p_i \ Q_i \ j \ \sum_{i2I} h \alpha_i, w_i \, i.Q_i$$

where $\mathbf{0}$ is the deadlock state, $\sum_{i2I} p_i \ Q_i$ represents a distribution that gives probability p_i to state Q_i, and $\sum_{i2I} h \alpha_i, w_i \, i.Q_i$ is a state that can nondeterministically evolve into state Q_i by performing action α_i with weight w_i. We prove by induction on the size of Q that if $P \ j \ Q \stackrel{\tau}{\Rightarrow}_w \varepsilon$ then w is nite.

- $Q \quad \mathbf{0}$. This is the base case. If $P \ j \ \mathbf{0} \stackrel{\tau}{\Rightarrow}_w \varepsilon$ then obviously we have $P \stackrel{\tau}{\Rightarrow}_w \varepsilon$. Since P is a bounded wMDP, we know that w is nite.
- $Q \quad \sum_{i2I} p_i \ Q_i$. If $(P \ j \ \sum_{i2I} p_i \ Q_i) \stackrel{\tau}{\Rightarrow}_w \varepsilon$, then we have $P \ j \ Q_i \stackrel{\tau}{\Rightarrow}_{w_i} \varepsilon$ and $w = \sum_{i2I} p_i w_i$. By induction hypothesis, each w_i is nite. It follows that w is also nite.
- $Q \quad \sum_{i2I} h \alpha_i, w_i \, i.Q_i$. Note that it is easy to see Q generates a nitary wMDP. By Theorem 2.20 it su ces to show that, for each static policy pp which determines the hyper-SP-derivation $P \ j \ Q \stackrel{\tau}{\Rightarrow}_{\mathrm{pp}, w} \varepsilon$, the weight w is nite, because the nite generability theorem ensures that the weight of a general hyper-derivation is the convex combination of the weights given by static policies. We prove this using a schema similar to that in the proof of Lemma 2.26.

  We call a state in the compound wMDP $P \ j \ Q$ *productive* if it is in the form $P^0 \ j \ Q$ and $\mathrm{pp}(P^0 \ j \ Q) = h w_i, P^{00} \ j \ Q_i \, i$ for some $i \in I$ and P^{00}. That is, Q has participated in the

transition $P' \mid Q \xrightarrow{\tau}_{w_i} P'' \mid Q_i$. We modify pp so as to obtain a static policy pp$'$ by setting pp$'(s)$ = pp(s) except when s is productive, in which case we set pp$'(s)$ ". The new policy determines a unique hyper-SP-derivation $P \mid Q \stackrel{\tau}{\Rightarrow}_{\mathsf{pp}',w_1}$ for some w_1 and , and induces a sub-wMDP from the wMDP induced by pp. The subdistribution is in the form $P' \mid Q$ because Q does not participate in any τ-transition in order to derive , and there is a hyper-derivation in P such that $P \stackrel{\tau}{\Rightarrow}_{w_1} P'$. Since P is bounded, we know that w_1 is nite. We split up into $_1$ + $_2$ so that each state in $d\ _2e$ is productive under policy pp and $_1$ is supported by all other states, if there are any at all. From $_2$ the policy pp determines the hyper-SP-derivation $_2 \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w_2} \varepsilon$ for some w_2. Then there are some w_{2s} such that $w_2 = \sum_{s2d\ _2e}\ _2(s)\ w_{2s}$ and $\overline{s} \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w_{2s}} \varepsilon$ for each s 2 $d\ _2e$. Since each state s in $d\ _2e$ is productive, it must be in the form $P_s \mid Q$ and make the transitions $P_s \mid Q \xrightarrow{\tau}_{w_s} P'' \mid Q_i \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w'_s} \varepsilon$ with $w_s + w'_s = w_{2s}$. By induction hypothesis, the weight w'_s is nite. Then w_{2s} is nite because w_s trivially is. It follows that w_2 is nite. Combining the two hyper-SP-derivations $P \mid Q \stackrel{\tau}{\Rightarrow}_{\mathsf{pp}',w_1}\ _1 +\ _2$ and $_2 \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w_2} \varepsilon$ we have $P \mid Q \stackrel{\tau}{\Rightarrow}_{\mathsf{pp}',w_1}\ _1 +\ _2 \stackrel{\tau}{\Rightarrow}_{\mathsf{pp},w_2}\ _1$. As we only divide the original hyper-SP-derivation into two stages, and does not change the τ transition from each state, the overall weight and the nal subdistribution will not change, thus we have $w_1 + w_2 = w$ and $_1 = \varepsilon$. Since both w_1 and w_2 are shown to be nite, it follows that w is nite as well.

3 Amortised weighted simulations

3.1 Introduction

Here we assume some wMDP $\langle S, \mathsf{Act}_\tau, \mathsf{R}_{\ 0}, \ ! \ \rangle$. Weighed simulations can be de ned either at the distribution level or at the state level. We choose the latter.

De nition 3.1 Given a relation $R \quad S \quad (\mathsf{R}_{\ 0} \quad D(S))$, let $S(R) \quad S \quad (\mathsf{R}_{\ 0} \quad D(S))$ be the relation de ned by letting $s\ S(R)\ \langle r, \ \rangle$ whenever

$s \xrightarrow{\alpha}! \ v$ implies the existence of some w and $'$ such that $\stackrel{\alpha}{\Rightarrow}_w\ '$ and $\overline{R}\ \langle r + w \quad v, \ ' \rangle$

The operator $S(\ )$ is monotonic and so it has a maximal xed point, which we denote by C. We often write $s\ \mathsf{C}_r$ for $s\ \mathsf{C}\ \langle r, \ \rangle$ and use v_{sim} to mean that there is some initial investment r such that $\overline{\mathsf{C}}_r$.

The basic idea here is that $s\ \mathsf{C}_r$ intuitively means that can simulate the actions of s but with *more bene t*, or at least not less bene t. The parameter r should be viewed as compensation which has accumulated which can be used in local comparisons between the bene ts of individual actions. Thus when we simulate $s \xrightarrow{\alpha}! \ v$ with $\stackrel{\alpha}{\Rightarrow}_w\ '$ there are two possibilities:

(i) $w > v$; here the accumulated compensation is increased from r to $r + (w \quad v)$. In subsequent rounds this extra compensation may be used to successfully simulate a heavier action with a lighter one.

(ii) w v; here the compensation is decreased from r to r $(v$ $w)$.

Finally it is important that r 0, and remains greater than or equal to zero, or otherwise the presence of weights would have no e ect. Thus in case (ii) if $(v$ $w) > r$ then the simulation is not successful.

We now show that with this formal de nition of the relation $\mathcal{R}_{sim}$ the various statements asserted in the Introduction are true:

Example 3.2 Consider the rst two systems, s_0 and t_0, viewed as wMDPs. Then the relation $\mathcal{R}$ given by

$$\mathcal{R} = \{(s_0, \{r, \overline{t_0}\}) \mid r \quad 1\} \cup \{(s_d, \{r, \overline{t_d}\}) \mid r \quad 0\}$$

is a simulation. Thus s_0 C$_r$ $\overline{t_0}$ for any r 1. As pointed out in [KAK05] this example shows the need for the parametrisation with respect to initial investments r; Because of the weights associated with the action up an initial investment of at least one is required in order for $\overline{t_0}$ to be able to match s_0.

We also have s_0 C$_r$ $\overline{s_1}$ for any r 1 because of the following simulation:

$$\mathcal{R} = \{(s_0, \{r, \overline{s_1}\}) \mid r \quad 1\} \cup \{(s_d, \{r, \quad\}) \mid r \quad 0\}$$

where is the distribution $\frac{1}{4}\ \overline{O} + \frac{3}{4}\ \overline{T}$. Note that this is indeed a simulation because $\overset{\text{down}}{\longrightarrow}_{2.5}\ \overline{s_1}$. Incidently this example shows why it is necessary to relate states to distributions, rather than states; there is no individual state accessible from s_1 which can simulate s_d.

Similarly s_1 C$_r$ $\overline{t_1}$ for every r 0 because of the simulation:

$$\mathcal{R} = \{(s_1, \{r, \overline{t_1}\}) \mid r \quad 0\} \cup \{(O, \{r, \overline{U}\}) \mid r \quad 0\} \cup \{(T, \{r, \overline{U}\}) \mid r \quad 0\}$$

Note that from Example 2.9 we have seen that $\overline{U} \Rightarrow_3 \overline{D}$ and therefore by transitivity $\overline{U} \overset{\text{down}}{\Rightarrow}_4 \overline{t_1}$.

Finally s_0 C$_2$ s_2 because of the following simulation:

$$\mathcal{R} = \{(s_0, \{r, \overline{s_2}\}) \mid r \quad 2\} \cup \{(s_d, \{r, \quad\}) \mid r \quad 0\}$$

where is the distribution $\frac{1}{4}\ \overline{S} + \frac{3}{4}\ \overline{T}$. Note that $\overset{\text{down}}{\Rightarrow}_3\ \overline{s_2}$ although it is also possible for it to do the down action for much less bene t.

Our rst result about the simulation preorder C is that its lifting $\overline{\text{C}}$ is a precongruence relation for the language CCMDP.

Lemma 3.3 1. If $\Rightarrow_r$ then $\Rightarrow_r$ and $\Rightarrow_r$.

2. If $\overset{a}{\longrightarrow}_{r_1}$ and $\overset{a}{\longrightarrow}_{r_2}$ then $\overset{\tau}{\longrightarrow}_{r_1+r_2}$.

Proof. Straightforward calculations.

Theorem 3.4 The relation $\overline{\text{C}}$ is a precongruence.

Proof. It is easy to verify that $\overline{\mathsf{C}}$ is closed under prefixing, nondeterministic choice, and hiding operators. Here we only show that the closure under parallel composition is also preserved, namely, if $\overline{\mathsf{C}}_r$ then $(\ \ |\ \ )\ \overline{\mathsf{C}}_r\ (\ \ |\ \ )$. We first construct the following relation

$$R := \{(s \mid t, \langle r, \ \ \rangle \mid t \mid i) \mid s\ \mathsf{C}_r\ \ \}$$

and check that R C. Suppose that $(s \mid t)\ R_r\ (\ \ |\ t)$.

If $s \mid t \xrightarrow{\alpha} {}_v\ \ |\ t$ because of the transition $s \xrightarrow{\alpha} {}_v\ \ $, then $\ \ \stackrel{\alpha}{\Rightarrow} {}_w\ \ '$ and $\ \ \overline{\mathsf{C}}_{r+w\ \ v}\ \ '$. By Lemma 3.3 we have $\ \ |\ t \stackrel{\alpha}{\Rightarrow} {}_w\ \ '\mid t$. It also holds that $(\ \ |\ t)\ \overline{R}_{r+w\ \ v}\ (\ \ '\mid t)$.

If $s \mid t \xrightarrow{\alpha} {}_v\ s \mid \ \ $ because of the transition $t \xrightarrow{\alpha} {}_v\ \ $, then $\ \ |\ t \xrightarrow{\alpha} {}_v\ \ \mid\ \ $ and we have that $(s \mid \ \ )\ \overline{R}_r\ (\ \ |\ \ )$.

If $s \mid t \xrightarrow{\tau} {}_v\ \ \mid\ \ $ because of the transitions $s \xrightarrow{a} {}_{v_1}\ \ $ and $t \xrightarrow{a} {}_{v_2}\ \ $ with $v = v_1 + v_2$, then $\ \ \stackrel{a}{\Rightarrow} {}_{w_1}\ \ '$ and $\ \ \overline{\mathsf{C}}_{r+w_1\ \ v_1}\ \ '$. By Lemma 3.3 we derive that $\ \ |\ t \stackrel{\tau}{\Rightarrow} {}_{w_1+v_2}\ \ '\mid\ \ $. Note that $r + (w_1 + v_2)\ \ (v_1 + v_2) = r + w_1\ \ v_1$ and $(\ \ |\ \ )\ \overline{R}_{r+w_1\ \ v_1}\ (\ \ '\mid\ \ )$.

So we have shown that R is a simulation relation. It follows that $\ \ \overline{\mathsf{C}}_r\ \ $ implies $(\ \ |\ \ )\ \overline{R}_r\ (\ \ |\ \ )$, thus $(\ \ |\ \ )\ \overline{\mathsf{C}}_r\ (\ \ |\ \ )$.

Example 3.5 Let P, Q be two processes with $P\ \mathsf{C}_0\ \overline{Q}$. Consider the following processes:

$$\begin{array}{lll} U & (& \tau_0.(\tau_1.U \ \tfrac{3}{4}\ \ \mathsf{down}_1.Q) \\ P' & & \mathsf{up}_2.(\mathsf{down}_1.P \ \tfrac{1}{4}\ \ \mathsf{down}_3.P) \\ Q' & & \mathsf{up}_2.U \end{array}$$

By the analysis in Example 2.9 we know that $\overline{U} \stackrel{\tau}{\Rightarrow} {}_3\ \overline{\mathsf{down}_1.Q}$, thus $\overline{U} \stackrel{\mathsf{down}}{\Rightarrow} {}_4\ \overline{Q}$. Then it is easy to see that $\mathsf{down}_1.P\ \mathsf{C}_0\ \overline{U}$ and $\mathsf{down}_3.P\ \mathsf{C}_0\ \overline{U}$. It follows from the compositionality of $\overline{\mathsf{C}}_0$ that $(\mathsf{down}_1.P \ \tfrac{1}{4}\ \ \mathsf{down}_3.P)\ \overline{\mathsf{C}}_0\ \overline{U}$ and furthermore $\overline{P'}\ \overline{\mathsf{C}}_0\ \overline{Q'}$.

Note that in Definition 3.1 for $s\ \mathsf{C}_r\ \ $ to be true we only require that strong moves from s be matched by weak moves from $\ \ $; this restriction makes the proof of the congruence result, Theorem 3.4, relatively straightforward. But later, in particular when giving a logical characterisation of the simulation preorder, it will be useful to know that this transfer property is also true for weak moves from s. We end this section with a proof of this result, which first requires a lemma.

Lemma 3.6 Let $\ \ $ and $\ \ $ be two subdistributions in a bounded wMDP. Suppose $\ \ \overline{\mathsf{C}}_r\ \ $ for some $r \in \mathsf{R}_0$. If $\ \ \xrightarrow{\alpha} {}_v\ \ '$ then $\ \ \stackrel{\alpha}{\Rightarrow} {}_w\ \ '$ for some w and $\ \ '$ such that $\ \ '\ \overline{\mathsf{C}}_{r+w\ \ v}\ \ '$.

Proof. Note that in the statement of the lemma both $\ \ $ and $\ \ $ are in general subdistributions. Although the relations C_r only relate states to full distributions, the lifted relations $\overline{\mathsf{C}}_r$ are relations over subdistributions.

Suppose $\ \ \overline{\mathsf{C}}_r\ \ $ and $\ \ \xrightarrow{\alpha} {}_v\ \ '$. By Lemma 2.3 there is an index set I such that (i) $\ \ = \sum_{i \in I} p_i\ \ \overline{s_i}$, (ii) $r = \sum_{i \in I} p_i r_i$, (iii) $\ \ = \sum_{i \in I} p_i\ \ _i$, and (iv) $s_i\ \mathsf{C}_{r_i}\ \ _i$ for each $i \in I$ with $\sum_{i \in I} p_i\ \ 1$. By the condition $\ \ \xrightarrow{\alpha} {}_v\ \ '$, (i) and Proposition 2.6, there are some weights v_i

and subdistributions μ'_i such that $v = \sum_{i \in I} p_i v_i$, $\mu' = \sum_{i \in I} p_i \mu'_i$, and $\overline{s_i} \xrightarrow{\alpha} \sum_{j \in J_i} q_{ij} v_{ij}$ for each $i \in I$. By Lemma 2.3 again, for each $i \in I$, there is an index set J_i such that $v_i = \sum_{j \in J_i} q_{ij} v_{ij}$, $\mu'_i = \sum_{j \in J_i} q_{ij} \mu'_{ij}$ and $s_i \xrightarrow{\alpha} v_{ij}$ μ'_{ij} for each $j \in J_i$ and $\sum_{j \in J_i} q_{ij} = 1$. By (iv) there is some w_{ij} and μ'_{ij} such that $\mu_i \xrightarrow{\alpha} w_{ij}$ μ'_{ij} and $\mu'_{ij} \, \overline{C}_{r_i + w_{ij}} \, v_{ij}$ μ'_{ij}. Let $w = \sum_{i \in I, j \in J_i} p_i q_{ij} w_{ij}$ and $\mu' = \sum_{i \in I, j \in J_i} p_i q_{ij} \mu'_{ij}$. By Proposition 2.11 the relation $\xrightarrow{\tau}$ is linear, from which it follows that $\xrightarrow{\alpha}$ is also linear for an arbitrary α. It follows that $\mu = \sum_{i \in I} p_i \sum_{j \in J_i} q_{ij} \mu_i \xrightarrow{\alpha} w \mu'$. By the linearity of $\overline{C}$, we conclude that $\mu' = (\sum_{i \in I} p_i \sum_{j \in J_i} q_{ij} \mu'_{ij}) \, \overline{C}_{r+w} \, v \mu'$.

Proposition 3.7 [Weak transfer property] Let s be a state and μ a distribution in a bounded wMDP such that $s \, C_r \, \mu$ for some $r \in \mathbb{R}_{\geq 0}$. Suppose $\overline{s} \xrightarrow{\alpha} v \mu'$ where μ' is again a distribution. Then $\mu \xrightarrow{\alpha} w \mu'$ for some w and μ' such that $\mu' \, \overline{C}_{r+w} \, v \mu'$.

Proof. Before embarking on the proof first note that we are assured that the matching μ' in the statement of the lemma is also a distribution. Using the characterisation in Lemma 2.3, it is easy to check that if $\overline{R} \langle r, \mu \rangle \langle r, \mu' \rangle$ for any relation $R \subseteq S \times (\mathbb{R}_{\geq 0} \times D(S))$ then $|\mu| = |\mu'|$. Since $\mu' \, \overline{C}_{r+w} \, v \mu'$ and μ' is a distribution it follows that μ' must also be a distribution.

We give the proof in the case when α is τ; the case for $a \in \mathrm{Act}$ follows from this in a straightforward manner. Suppose $s \, C_r \, \mu$ and $\overline{s} \xrightarrow{\tau} v \mu'$ with $|\mu'| = 1$. So there are μ_k, μ'_k and r_k for $k \geq 0$ such that $\overline{s} = \mu_0$, $\mu_k = \mu'_k + \mu_{k+1}$, $\mu'_k \xrightarrow{\tau} v_{k+1} \mu_{k+1}$, $v = \sum_{k=1}^{\infty} v_k$ and $\mu' = \sum_{k=0}^{\infty} \mu'_k$. Since $\mu'_0 + \mu_0 = \overline{s} \, \overline{C}_r \, \mu$, by Proposition 2.6 we can make the decomposition $\mu = \mu'_0 + \mu_0$ so that $\mu'_0 \, \overline{C}_{r'_0} \, \mu'_0$ and $\mu_0 \, \overline{C}_{r''_0} \, \mu_0$ for some r'_0, r''_0 with $r'_0 + r''_0 = r$. Since $\mu'_0 \xrightarrow{\tau} v_1 \mu_1$ and $\mu'_0 \, \overline{C}_{r'_0} \, \mu'_0$, by Lemma 3.6 we have $\mu'_0 \xrightarrow{\tau} w_1 \mu_1$ with $\mu_1 \, \overline{C}_{(r'_0 + w_1 \, v_1)} \, \mu_1$.

Repeating the above procedure gives us inductively a series μ_k, μ'_k, μ_k of subdistributions, for $k \geq 0$, and weights r'_k, r_k, for $k \geq 1$, such that $\mu = \mu_0$, $\mu_k \, \overline{C}_{(r'_{k-1} + w_k \, v_k)} \, \mu_k$, $\mu_k = \mu'_k + \mu_k$, $\mu'_k \, \overline{C}_{r'_k} \, \mu'_k$, $\mu_k \, \overline{C}_{r''_k} \, \mu_k$, $\mu'_k \xrightarrow{\tau} w_{k+1} \mu_{k+1}$ and $r'_{k-1} + w_k \, v_k = r'_k + r_k$. We define $\mu' = \sum_{k=0}^{\infty} \mu'_k$, $w = \sum_{k=1}^{\infty} w_k$ and $r' = \sum_{k=0}^{\infty} r_k$. It follows from Definition 2.2 that $\mu \, \overline{C}_{r'} \, \mu'$. Below we show that $\mu \xrightarrow{\tau} w \mu'$ and $r' = r + w \, v$.

By the transitivity of hyper-derivations, Theorem 2.13, it can be established that $\mu \xrightarrow{\tau} \sum_{k \leq i} w_k$ $(\mu'_i + \sum_{k \, i} \mu_k)$ for each $i \geq 0$. Since $|\mu'| = 1$, we must have $\lim_{i \to \infty} |\mu'_i| = 0$. Again using the characterisation in Lemma 2.3 we know that $|\mu'_i| = |\mu_i|$ for each i. Therefore, since $\mu'_i \, \overline{C}_{r'_i} \, \mu'_i$, we then have $\lim_{i \to \infty} \sum |\mu'_i| = 0$. Thus, $\lim_{i \to \infty} (\mu'_i + \sum_{k \, i} \mu_k) = \sum_{k=0}^{\infty} \mu_k = \mu'$. We also have $\lim_{i \to \infty} \sum_{k \, i} w_k = \sum_{k=1}^{\infty} w_k = w$. In Appendix C, specifically in Corollary C.1, we show that the set $\{\langle v, \mu \rangle \mid \mu \xrightarrow{\tau} v \mu\}$ is compact. From this it follows that $\mu \xrightarrow{\tau} w \mu'$.

By an easy inductive proof it can be seen that $r = r'_i + \sum_{k \, i} r_k + \sum_{k<i} v_k \sum_{k<i} w_k$ for each $i \geq 0$. From $\lim_{i \to \infty} \sum |\mu'_i| = 0$ and $\mu'_i \, \overline{C}_{r'_i} \, \mu'_i$ it follows that $\lim_{i \to \infty} r'_i = 0$. Therefore, $r = \sum_{k \geq 0} r_k + \sum_{k \geq 0} v_k \sum_{k \geq 0} w_k = r' + v \, w$, i.e. $r' = r + w \, v$.

This weak transfer property is easily generalised to distributions:

Corollary 3.8 Suppose $\mu \, C_r \, \nu$ for some $r \in \mathbb{R}_{\geq 0}$, where μ, ν are two distributions in a bounded wMDP. If $\mu \xrightarrow{\alpha} v \mu'$, where μ' is also a distribution, then there exists a distribution ν' such that $\nu \xrightarrow{\alpha} w \nu'$ and $\mu' \, \overline{C}_{r+w} \, v \nu'$.

Proof. Combining Proposition 2.11 and Proposition 3.7.

3.2 In nite approximation

The simulation relations C_r are de ned coinductively. But in bounded wMDPs they can also be characterised inductively.

De nition 3.9 For every k 0 we de ne the relation C^k S (R $_0$ $D(S)$) as follows:

(i) $C^0 = S$ (R $_0$ $D(S)$)

(ii) $C^{k+1} = S(C^k)$.

Finally we let C^1 be $\bigcap_{k=0}^{1} C^k$.

Standard arguments ensure that C_r C_r^k for every k 0 and therefore that C_r C_r^1. The converse is also true in bounded wMDPs, as we now demonstrate, using compactness arguments.

We note that the metric space (R $_0$ $D_{sub}(S), d_1$) equipped with the distance function

$$d_1(hv, \quad i, hw, \quad i) = \max(fjw \quad vjg \; [\; fj \quad (s) \qquad (s)j \quad j \; s \; 2 \; Sg)$$

is complete. Provided the set S is nite, the distance function on the space (S ! R $_0$ $D_{sub}(S), d_2$) given by $d_2(f, g) = \max_{s2S} d_1(f(s), g(s))$ is well-de ned, and the resulting metric space is also complete.

Proposition 3.10 For any subdistribution in a bounded wMDP the set $fhw, \quad {}^0 i \; j \quad =^{\alpha})_w \quad {}^0 g$ is closed.

Proof. See Appendix C; a more general result is given in Lemma C.6.

De nition 3.11 A relation R S (R $_0$ $D_{sub}(S)$) is *closed* (resp. *bounded*) if for every s 2 S the set s $R = fhw, \quad i \; j \; s \; R \; hw, \quad i \; g$ is closed (resp. bounded). It is *compact* if it is both closed and bounded.

The main technical result we require is the following:

Proposition 3.12 In a bounded wMDP, for every k 2 N, the relation C^k is closed and convex.

Proof. Because of the style of argument required this proof is also relegated to Appendix C.

Before the main result of this section we need one more technical result.

Lemma 3.13 Let S be a nite set of states. Suppose R^k S (R $_0$ $D_{sub}(S)$) is a sequence of closed and convex relations such that $R^{(k+1)}$ R^k. Then it holds that

$$(\bigcap_{k=0}^{1} \overline{R^k}) \qquad \overline{(\bigcap_{k=0}^{1} R^k)} \; .$$

Proof. Let R^1 denote $(\setminus_{k=0}^{1} R^k)$, and suppose $\overline{R^k}\ \hbar w,\ \ i$ for every $k\ \ 0$. We have to show that $\overline{R^1}\ \hbar w,\ \ i$.

Since R^k is closed and convex for each k, it follows that R^1 is also closed and convex. Moreover it is easy to check that the set of choice functions $\mathrm{Ch}(R)$ is also closed. Therefore, $\mathrm{Ch}(R^k)$ for each $k\ 2$ N and $\mathrm{Ch}(R^1)$ are closed.

Now consider

$$G = f\, f : S\ \ !\ \ \mathrm{R}_0\ \ D_{sub}(S)\ j\ \hbar w,\ \ i = \mathrm{Exp}\ \ (f)\, g$$

which is easily seen to be a closed set. Consider the collection of closed sets $H^k = \mathrm{Ch}(R^k) \setminus G$; since $\overline{R^k}\ \hbar w,\ \ i$, Proposition 2.5 assures us that all of these are non-empty. Also $H^{(k+1)}\ \ H^k$ and therefore by the nite-intersection property [Lip65] $\setminus_{k=0}^{1} H^k$ is also non-empty.

Let f be an arbitrary element of this intersection. For any state $s\ 2\ \mathrm{dom}(R^1)$, and for every $k\ \ 0$, we have $s\ 2\ \mathrm{dom}(R^k)$ because $\mathrm{dom}(R^1)\ \ \mathrm{dom}(R^k)$. Therefore, $s\ R^k\ f(s)$ as $f\ 2\ \mathrm{Ch}(R^k)$. It follows that $s\ R^1\ f(s)$. So f is a choice function for R^1, $f\ 2\ \mathrm{Ch}(R^1)$. From Proposition 2.5 it follows that $\overline{R^1}\ \mathrm{Exp}\ \ (f)$. But from the de nition of the G we know that $\hbar w,\ \ i = \mathrm{Exp}\ \ (f)$, and the required result follows.

Theorem 3.14 In a bounded wMDP, $s\ \mathrm{C}_r$ if and only if $s\ \mathrm{C}_r^1$.

Proof. Since $\mathrm{C}\ \ \mathrm{C}^1$ it is su cient to show the opposite inclusion, which by de nition holds if C^1 is a simulation, viz. if $\mathrm{C}^1\ \ S(\mathrm{C}^1)$. Suppose $s\ \mathrm{C}_r^1$, which means that $s\ \mathrm{C}_r^k$ for every $k\ \ 0$. In order to show $s\ S(\mathrm{C}^1)_r$ we have to establish that if $s\ \ {}^{\alpha}!_{v}\ \ {}^{0}$ then $\ \ {}^{\alpha}\!=\!)_{w}\ \ {}^{0}$ for some ^{0} such that ${}^{0}\ \overline{\mathrm{C}^1}_{(r+w\ \ v)}\ \ {}^{0}$.

For every $k\ \ 0$ there exists some $w_k,\ \ {}^{0}_{k}$ such that $\ \ {}^{\alpha}\!=\!)_{w_k}\ \ {}^{0}_{k}$ and ${}^{0}\ \overline{\mathrm{C}^k}_{(r+w_k\ \ v)}\ \ {}^{0}_{k}$. Now construct the sets

$$D^k = f\hbar w,\ \ {}^{0}i\ j\ \ \ {}^{\alpha}\!=\!)_{w}\ \ {}^{0} \text{ and } {}^{0}\ \overline{\mathrm{C}^k}_{(r+w\ \ v)}\ \ {}^{0}g.$$

We now argue that each D^k is a closed set.

To do so we rewrite it to a form which makes the fact that it is closed obvious. First de ne the function $E : D_{sub}(S)\ \ (S\ \ !\ \ \mathrm{R}_0\ \ D_{sub}(S))\ \ !\ \ \mathrm{R}_0\ \ D_{sub}(S)$ by $E(\ \ , f) = \mathrm{Exp}\ \ (f)$, which is obviously continuous. It is also a closed function, meaning that the image of every closed set under E is closed, because positive scaling and sum are operations that preserve closedness of functions. Because of Proposition 2.5 it can be shown that

$$D^k = (\ \ {}^{\alpha}\!=\!)\ )\setminus G\ \ {}^{1}\ \ E(f\ \ {}^{0}g\ \ \mathrm{Ch}(\mathrm{C}^k)),$$

where $G(\hbar w,\ \ {}^{0}i) = \hbar r + w\ \ v,\ \ {}^{0}i$. Thus by Proposition 3.10 and Proposition 3.12 they are closed.

They are also non-empty and $D^{k+1}\ \ D^k$. So by the nite-intersection property the set $\mathrm{T}_{k=0}^{1} D^k$ is non-empty. For any $\hbar w,\ \ {}^{0}i$ in it we know $\ \ {}^{\alpha}\!=\!)_{w}\ \ {}^{0}$ and ${}^{0}\ \overline{\mathrm{C}^k}_{(r+w\ \ v)}\ \ {}^{0}$ for every $k\ \ 0$; that is ${}^{0}(\setminus_{k=0}^{1}\ \overline{\mathrm{C}^k}_{(r+w\ \ v)})\ \ {}^{0}$. By Proposition 3.12, the relations C^k are all closed and convex. Therefore, Lemma 3.13 may be applied to them, which enables us to conclude ${}^{0}\ \overline{\mathrm{C}^1}_{(r+w\ \ v)}\ \ {}^{0}$.

3.3 Modal logic

As part of our argument in favour of amortised simulations for wMDPs we show that it has associated with it a natural property or modal logic. We show two results. The rst is that a nitary version characterises the behavioural preorders C_r. Secondly we show that with the addition of xed points we can capture logically the behaviour of any state. Both results are restricted to bounded wMDPs.

Here we develop a modal logic which characterises the relations C_r^1 in an arbitrary wMDP, and thus C_r in bounded wMDPs.

Let L be the set of modal formulae de ned inductively as follows:

tt $2\ L$

$h\alpha i_w(\phi_1\ {}_p\ \ \phi_2)\ 2\ L$ when $\phi_i\ 2\ L$, $\alpha\ 2$ Act_τ, $w\ 2$ $\mathrm{R}\ {}_0$ and $p\ 2\ [0,1]$

$\phi_1 \wedge \phi_2\ 2\ L$ when $\phi_1,\ \phi_2\ 2\ L$

Let Con denote the set of all pairs $hr,\ \ i$, called *con gurations*, where $r\ 2$ $\mathrm{R}\ {}_0$ and $\ \ 2\ D(S)$, with S denoting the state space of some wMDP. Intuitively this represents a probabilistic system which has accumulated compensation r which it can use to satisfy formulae in the future. The satisfaction relation $j=\ \ Con\ \ L$ is now given by:

(i) $hr,\ \ i\ j=$ tt for every con guration

(ii) $hr,\ \ i\ j= \phi_1 \wedge \phi_2$ whenever $hr,\ \ i\ j= \phi_1$ and $hr,\ \ i\ j= \phi_2$

(iii) $hr,\ \ i\ j= h\alpha i_v(\phi_1\ {}_p\ \ \phi_2)$ whenever $\ \ =^{\alpha})\ {}_w\ \ {}^0$, $hr + w\ \ v,\ \ {}^0 i\ =\ hr_1,\ \ {}^0_1 i\ {}_p\ \ hr_2,\ \ {}^0_2 i$, and $hr_i,\ \ {}^0_i i\ j= \phi_i$.

Let $L(r,\ \ ) = f\ \phi\ 2\ L\ j\ hr,\ \ i\ j= \phi g$.

The idea here is that $hr,\ \ i$ represents a process which has built up compensation r which it can use to help satisfy a formula. The principal formula is $h\alpha i_v\phi$ which represents the ability to do an α action with bene t at least v and then satisfy ϕ. In (iii) above when this is satis ed by $hr,\ \ i$ because $\ \ =^{\alpha})\ {}_w\ \ {}^0$ there are two possibilities:

(i) $v > w$: here the compensation comes into play. The action may be accepted despite being too heavy but the compensation is reduced from r to $r\ \ (v\ \ w)$; note this is only possible if this sum $r\ \ (v\ \ w)\ \ 0$.

(ii) $v\ \ w$: The action is accepted and the compensation is increased from r to $r + (w\ \ v)$.

For convenience of presentation, we generalise binary probabilistic choice to be n-ary and often write $h\alpha i_w\ \ {}^{L}_{i2I}\, p_i\ \ \phi_i$ for nite index set I. It is easy to see that, for instance,

$$hr,\ \ i\ j= h\alpha i_w\ \ {}^{M}_{i=1..3}\ \ p_i\ \ \phi_i \quad \text{if and only if} \quad hr,\ \ i\ j= h\alpha i_w(\phi_1\ {}_{p_1}\ \ (h\tau i_0(\phi_2\ {}_{\frac{p_2}{1-p_1}}\ \ \phi_3)))$$

for any con guration $hr,\ \ i$.

The modal logic L has a limited number of operators, and for this reason the satisfaction relation is in some sense impervious to hyper-derivations:

Lemma 3.15 Suppose $\stackrel{\tau}{\Rightarrow}_w$ and $r + w \; r'$. Then $\langle r', \rangle \models \phi$ implies $\langle r, \rangle \models \phi$.

Proof. By structural induction on ϕ.

Proposition 3.16 Suppose in a bounded wMDP that $\overline{C}_r$. Then for every $\phi \in \mathcal{L}$, $\langle r , \rangle \models \phi$ implies $\langle r + r, \rangle \models \phi$.

Proof. By structural induction on ϕ.

ϕ tt. This case is trivial.

ϕ $\phi_1 \wedge \phi_2 \in \mathcal{L}$ we appeal to induction hypothesis directly.

ϕ $\langle\alpha\rangle_c(\phi_1 \; _p \; \phi_2)$. Suppose $\langle r , \rangle \models \phi$. This means $\stackrel{\alpha}{\Rightarrow}_v$, $\langle r + v \; c, \rangle = \langle r_1, \; _1 \; _p \; \langle r_2, \; _2\rangle$, and $\langle r_i, \; _i\rangle \models \phi_i$ for $i = 1, 2$. Note that by the definition of the satisfaction relation $\models$ we know that , $\in \mathcal{D}(S)$, i.e. $\; = 1$. In a bounded wMDP we know from Corollary 3.8 that $\overline{C}_r$ also satisfies the transfer property for weak moves and therefore $\stackrel{\alpha}{\Rightarrow}_w$ such that $\overline{C}_{(r+w \; v)}$. By Proposition 2.6, $\langle r + w \; v, \rangle = \langle t_1, \; _1 \; _p \; \langle t_2, \; _2\rangle$ so that $\overline{C}_{t_i} \; _i$ for $i = 1, 2$. By induction hypothesis, we have $\langle r_i + t_i, \; _i\rangle \models \phi_i$ for $i = 1, 2$. Since

$$(r_1 + t_1) \; _p \; (r_2 + t_2) = (r + v \; c) + (r + w \; v) = (r + r) + w \; c$$

it follows that $\langle r + r, \rangle \models \phi$.

Theorem 3.17 In a bounded wMDP, $L(0, \overline{s}) \; L(r, \;)$ implies $\overline{s} \; \overline{C}_r$.

Proof. Since we assume the wMDP is bounded, by Theorem 3.14 it is sufficient to prove the result for C^1 rather than C. Thus we have to show that for every $k \; 0$, $L(0, \overline{s}) \; L(r, \;)$ implies $\overline{s} \; \overline{C^k}_r$. This will follow immediately if for every state s and every index k we can construct the k-th *characteristic formulae* ϕ_s^k satisfying:

(a) $\langle 0, \overline{s}\rangle \models \phi_s^k$

(b) $\langle r, \rangle \models \phi_s^k$ implies $s \; C_r^k$.

The construction is by induction on k:

(i) $\phi_s^0 =$ tt

(ii) $\phi_s^{(k+1)} = \bigwedge_{s \; ! \; w} \langle\alpha\rangle_w \phi^k$

(iii) $\phi^k = \bigwedge_{s2d \; e} (s) \; \phi_s^k$.

The proof that properties (a) and (b) are satis ed proceeds by induction on k, with the case $k = 0$ being trivial. As an example of the inductive case we rst show $hr, \ i \ j= \phi_s^{(k+1)}$ implies $s \ C_r^{(k+1)}$.

So let us assume $hr, \ i \ j= \phi_s^{(k+1)}$. Let $s \ ^{\alpha}! \ _v$ be an arbitrary move from s; because of the construction of the characteristic formula we have that $hr, \ i \ j= h\alpha i_v \phi^k$. By de nition this means $=^{\alpha}) \ _w \ ^0$, where $h(r + w \ v), \ ^0 i = \ P_{s2d \ e} \ (s) \ hr_s, \ ^0_s i$ and $hr_s, \ ^0_s i \ j= \phi_s^k$. At this point we invoke induction to obtain $s \ C_{r_s}^k \ ^0_s$ from which it follows by the de nition of lifting that $\overline{C_{(r+w \ v)}^k} \ ^0$. Therefore, we have veri ed that $s \ C_r^{(k+1)}$.

As an immediate corollary we have a logical characterisation of our simulation preorder.

Corollary 3.18 In a bounded wMDP, $\overline{s} \ \overline{C}_r$ if and only if $L(0, \overline{s}) \quad L(r, \ )$.

Proof. Combining Proposition 3.16 and Theorem 3.17.

We now turn our attention to **characteristic formulae.** To this end we extend the modal logic L with a xed point operator.

Let *Var* be a countable set of variables. We de ne a set $L_{\mathtt{fix}}$ of modal formulae by the following grammar:

$$\phi \ := \ \mathrm{tt} \ j \ h\alpha i_w(\phi_{1 \ p} \quad \phi_2) \ j \ \phi_1 \ \wedge \ \phi_2 \ j \ X \ j \ \max X.\phi$$

where $\alpha \ 2 \ \mathrm{Act}_\tau \ w \ 2 \ R \ _0$ and $p \ 2 \ [0,1]$. Sometimes we also use the nite conjunction $\bigvee_{i2I} \phi_i$. As usual, we have $\bigvee_{i2;} \phi_i = \mathrm{tt}$. The xed point operator $\max X$ binds the variable X. We apply the usual terminology of free and bound variables in a formula and write $fv(\phi)$ for the set of free variables in ϕ.

We use *environments*, which binds free variables to sets of distributions, in order to give semantics to formulae. We x a bound wMDP and let S be its state set. Let

$$Env = f \ \rho \ j \ \rho : Var \ ! \ P(R \ _0 \quad D(S)) \ g$$

be the set of all environments and ranged over by ρ. For a set $V \quad R \ _0 \quad D(S)$ and a variable $X \ 2 \ Var$, we write $\rho[X \ 7! \ V]$ for the environment that maps X to V and Y to $\rho(Y)$ for all $Y \ 6= X$.

The semantics of a formula ϕ can be given as the set of con gurations satisfying it. This entails a semantic functional $[\![\ ]\!] : L_{\mathtt{fix}} \ ! \ Env \ ! \ P(R \ _0 \quad D(S))$ de ned inductively in Figure 5. As the meaning of a closed formula ϕ does not depend on the environment, we write $[\![\phi]\!]$ for $[\![\phi]\!]_\rho$ where ρ is an arbitrary environment.

The semantics of the xed point logic is similar to that of the modal mu-calculus [Koz83], but formulae are now satis ed by con gurations. The characterisation of *greatest xed point formula* $\max X.\phi$ follows from the well-known Knaster-Tarski xed point theorem [Tar55].

We shall consider (closed) *equation systems* of formulae of the form

$$\begin{aligned} E : X_1 &= \phi_1 \\ &\vdots \\ X_n &= \phi_n \end{aligned}$$

$$
\begin{array}{rcl}
[\![\mathsf{tt}]\!]_\rho & = & \mathsf{R}_0 \quad D(S) \\
[\![\phi_1 \wedge \phi_2]\!]_\rho & = & [\![\phi_1]\!]_\rho \setminus [\![\phi_2]\!]_\rho \\
[\![h\alpha i_v(\phi_1 \ p \quad \phi_2)]\!]_\rho & = & f\, h\, r, \quad i\ 2\ \mathsf{R}_0 \quad D(S)\ j\ 9\ ^0 : \quad =^{\alpha})_w \quad ^0 \text{ and} \\
 & & h\, r + w \quad v, \quad ^0 i = h\, r_1, \quad _1 i_p \quad h\, r_2, \quad _2 i \text{ with } h\, r_i, \quad _i i\ 2\ [\![\phi_i]\!]_\rho\, g \\
[\![X]\!]_\rho & = & \rho(X) \\
[\![\max X.\phi]\!]_\rho & = & \mathsf{S}\, f\, V \quad \mathsf{R}_0 \quad D(S)\ j\ V \quad [\![\phi]\!]_{\rho[X \mathbin{?} V]}\, g
\end{array}
$$

Figure 5: Semantics of the xed point logic

where $X_1, ..., X_n$ are mutually distinct variables and $\phi_1, ..., \phi_n$ are formulae having at most $X_1, ..., X_n$ as free variables. Here E can be viewed as a function E : *Var* ! $L_{\mathtt{fix}}$ de ned by $E(X_i) = \phi_i$ for $i = 1, ..., n$ and $E(Y) = Y$ for other variables Y *2 Var*.

An environment ρ is a *solution* of an equation system E if $8i : \rho(X_i) = [\![\phi_i]\!]_\rho$. The existence of solutions for an equation system can be seen from the following arguments. The set *Env*, which includes all candidates for solutions, together with the partial order de ned by

$$\rho \quad \rho^0 \text{ i } \quad 8X\ 2\ Var : \rho(X) \quad \rho^0(X)$$

forms a complete lattice. The *equation functional* E : *Env* ! *Env* given in the λ-calculus notation by

$$E := \lambda\rho.\lambda X.[\![E(X)]\!]_\rho$$

is monotonic. Thus, the Knaster-Tarski xed point theorem guarantees existence of solutions, and the largest solution

$$\rho_E := \mathsf{G}\, f\, \rho\ j\ \rho \quad E(\rho)\, g.$$

We rst observe that Proposition 3.16 can be generalised to this xed point logic $L_{\mathtt{fix}}$.

Let $f : L$! L be a monotonic function over a complete lattice L. For every ordinal λ de ne f^λ by:

$f^0 = >_L$, where $>_L$ is the greatest element of the lattice

$f^{\lambda+1} = f(f^\lambda)$

if λ is a limit ordinal let $f^\lambda = \bigsqcap f f^\beta\ j\ \beta < \lambda g$.

Theorem 3.19 [Tarski] There exists an ordinal λ such that f^λ is the greatest xed point of f.

A subset C of Con is *upper-closed (UC)* if $hr \quad , \quad i\ 2\ C$ and $\quad \overline{C}_r \quad$ implies $hr \quad + r, \quad i\ 2\ C$. An environment ρ is UC if $\rho(X)$ is UC for every variable X *2 Var*.

Theorem 3.20 If ρ is UC then so is $[\![\phi]\!]_\rho$ for every formula ϕ *2* $L_{\mathtt{fix}}$.

Proof. We proceed by structural induction on the formula ϕ. The case for $h\alpha i_r \phi^0$ is similar to the proof in Proposition 3.16. All other cases are straightforward except for the greast xed point.

Let $\phi = \max X.\phi^0$. Note that by structural induction we can assume that the result holds for ϕ^0. For every ordinal λ we de ne the set C^λ as follows:

(i) $C^0 = \mathsf{R}_0 \quad D(S)$

(ii) $C^{\lambda+1} = [\![\phi^0]\!]_{\rho[X := C]}$

(iii) $C^\lambda = \bigcap \{C^\beta \mid \beta < \lambda\}$ if λ is a limit ordinal.

By Tarski's theorem there is some ordinal λ such that $C^\lambda = [\![\phi]\!]_\rho$. So it is sufficient to prove, by induction over the ordinals, that C^λ is UC for every λ.

Case (i) is trivial. Case (ii) follows by structural induction, since by the inner induction the environment $\rho[x := C^\lambda]$ is UC. Case (iii) is trivial since the collection of UC sets are closed under intersection.

Corollary 3.21 Suppose in a bounded wMDP that $\overline{\mathsf{C}}_r$. Then for every closed formula $\phi \in L_{\mathtt{fix}}$, $\langle r, \rangle i \in [\![\phi]\!]$ implies $\langle r + r, \rangle i \in [\![\phi]\!]$.

Let $L_{\mathtt{fix}}(r,) = \{\phi \in L_{\mathtt{fix}} \mid fv(\phi) = ; \wedge \langle r, \rangle i \models \phi\}$. Then we have the extension of Corollary 3.18 from L to $L_{\mathtt{fix}}$.

Corollary 3.22 In a bounded wMDP, $\overline{s}\ \overline{\mathsf{C}}_r$ if and only if $L_{\mathtt{fix}}(0, \overline{s}) \quad L_{\mathtt{fix}}(r,)$.

Proof. It follows from Corollary 3.21 and Theorem 3.17.

Below we characterise the behaviour of a process by an equation system of modal formulae. To do so it will be convenient to use a generalised modality operator of the form $\langle\alpha\rangle_w \bigwedge_{i\in I} p_i \to \phi_i$ where I is a finite index set I. The satisfaction relation can be extended to these formulae so that they become derived operators in the language $L_{\mathtt{fix}}$, as we did in L.

Definition 3.23 Given a bounded wMDP, its *characteristic equation system* consists of one equation for each state $s_1, ..., s_n \in S$.

$$\begin{aligned} E : X_{s_1} &= \phi_{s_1} \\ &\vdots \\ X_{s_n} &= \phi_{s_n} \end{aligned}$$

where

$$\phi_s := \bigwedge_{s \xrightarrow{\ } v} \langle\alpha\rangle_v X \tag{3}$$

with $X := \bigwedge_{s \in d\ e} (s) \ X_s$.

Theorem 3.24 Suppose E is a characteristic equation system. Then $s\ \mathsf{C}_r$ if and only if $\langle r, \rangle i \in \rho_E(X_s)$.

Proof. (( ) Let $R := \{(s, \langle r, \rangle i) \mid \langle r, \rangle i \in \rho_E(X_s)\}$. We first show that

$$\langle r, \rangle i \in [\![X\ ]\!]_{\rho_E} \text{ implies } \quad \overline{R}\ \langle r, \rangle i. \tag{4}$$

Let $= \bigwedge_{i2I} p_i \ \overline{s_i}$, then $X = \bigwedge_{i2I} p_i \ X_{s_i}$. Suppose $hr, \ i \ 2 \ [\![X \ ]\!]_{\rho_E}$. We have that $hr, \ i = \bigvee_{i2I} p_i \ hr_i, \ _i i$ and, for all $i \ 2 \ I$, $hr_i, \ _i i \ 2 \ [\![X_{s_i}]\!]_{\rho_E}$, i.e. $s_i \ R \ hr_i, \ _i i$. It follows that $\overline{R} \ hr, \ i$.

Now we show that R is an amortised weighted simulation. Suppose $s \ R \ hr, \ i$ and $s \ \stackrel{\alpha}{!}_v$. Then $hr, \ i \ 2 \ \rho_E(X_s) = [\![\phi_s]\!]_{\rho_E}$. It follows from (3) that $hr, \ i \ 2 \ [\![h\alpha i_v X \ ]\!]_{\rho_E}$. So there exists some ^{0} such that $\stackrel{\alpha}{=}) \ _w \ ^0$ and $hr + w \ v, \ ^0 i \ 2 \ [\![X \ ]\!]_{\rho_E}$. Now we apply (4).

( )) We de ne the environment ρ by

$$\rho(X_s) := f hr, \ i \ j \ s \ C_r \ g.$$

It su ces to show that ρ is a post- xed point of E, i.e.

$$\rho \ E(\rho) \tag{5}$$

because in that case we have $\rho \ \rho_E$, thus $s \ C \ hr, \ i$ implies $hr, \ i \ 2 \ \rho(X_s)$ which in turn implies $hr, \ i \ 2 \ \rho_E(X_s)$.

We rst show that

$$\overline{C} \ hr, \ i \text{ implies } hr, \ i \ 2 \ [\![X \ ]\!]_\rho. \tag{6}$$

Suppose $\overline{C} \ hr, \ i$. Then we have that (i) $= \bigvee_{i2I} p_i \ \overline{s_i}$, (ii) $hr, \ i = \bigvee_{i2I} p_i \ hr_i, \ _i i$, (iii) $s_i \ C \ hr_i, \ _i i$ for all $i \ 2 \ I$. We know from (iii) that $hr_i, \ _i i \ 2 \ [\![X_{s_i}]\!]_\rho$. Using (ii) we have that $hr, \ i \ 2 \ [\![\bigwedge_{i2I} p_i \ X_{s_i}]\!]_\rho$. Using (i) we obtain $hr, \ i \ 2 \ [\![X \ ]\!]_\rho$.

Now we are in a position to show (5). Suppose $hr, \ i \ 2 \ \rho(X_s)$. We must prove that $hr, \ i \ 2 \ [\![\phi_s]\!]_\rho$, i.e.

$$hr, \ i \ 2 \bigcap_{s \ !_v} [\![h\alpha i_v X \ ]\!]_\rho$$

by (3).

We assume that $s \ \stackrel{\alpha}{!}_v$. Since $s \ C_r$, there exists some ^{0} such that $\stackrel{\alpha}{=}) \ _w \ ^0$ and $\overline{C} \ hr + w \ v, \ ^0 i$. By (6), we get $hr + w \ v, \ ^0 i \ 2 \ [\![X \ ]\!]_\rho$. It follows that $hr, \ i \ 2 \ [\![ha i_v X \ ]\!]_\rho$.

So far we know how to construct the characteristic equation system for a bounded wMDP. As introduced in [MO98], the three transformation rules in Figure 6 can be used to obtain from an equation system E a formula whose interpretation coincides with the interpretation of X_1 in the greatest solution of E. The formula thus obtained from a characteristic equation system is called a *characteristic formula*.

Theorem 3.25 Given a characteristic equation system E, there is a characteristic formula ϕ_s such that $\rho_E(X_s) = [\![\phi_s]\!]$ for any state s.

The above theorem, together with Theorem 3.24, gives rise to the following corollary.

Corollary 3.26 For each state s in a bounded wMDP, there is a characteristic formula ϕ_s such that $s \ C \ hr, \ i$ i $hr, \ i \ 2 \ [\![\phi_s]\!]$.

1. Rule 1: $E \;!\; F$
2. Rule 2: $E \;!\; G$
3. Rule 3: $E \;!\; H$ if $X_n \in fv(\phi_1, ..., \phi_n)$

$$
\begin{array}{llll}
E : X_1 = \phi_1 & F : X_1 = \phi_1 & G : X_1 = \phi_1[\phi_n/X_n] & H : X_1 = \phi_1 \\
\quad\vdots & \quad\vdots & \quad\vdots & \quad\vdots \\
X_{n-1} = \phi_{n-1} & X_{n-1} = \phi_{n-1} & X_{n-1} = \phi_{n-1}[\phi_n/X_n] & X_{n-1} = \phi_{n-1} \\
X_n = \phi_n & X_n = \max X_n.\phi_n & X_n = \phi_n &
\end{array}
$$

Figure 6: Transformation rules

4 Testing

4.1 Benefits testing

Standard theories of testing involve the idea of applying tests to processes and seeing if the result is a *success*. With the presence of weights on wMDPs we have a more elementary way of testing; we run a test in parallel with the process being tested and calculate the possible benefits which can be accrued. Then two wMDPs can be compared via the resulting sets of possible benefits.

Definition 4.1 A wMDP of the form $\langle S, Act \cup \{\tau\}, W, \rightarrow \rangle$ is referred to as a *(weighted) computation structure*.

An arbitrary wMDP can be viewed as a weighted computation structure by ignoring all the actions $s \xrightarrow{a} w$ other than $s \xrightarrow{\tau} w$; indeed weighted computation structures correspond more or less directly with the more standard notion of *Markov decision processes*. Here we are interested in the computation structures generated by wMDPs of the form

$$[\![P]\!] \parallel [\![T]\!]$$

where P is a wMDP which we wish to investigate and T is a finite wMDP, representing the investigation. The question now is how do we associate a set of possible rewards with a distribution over the set of states of a weighted computation structure?

Consider the simple fully probabilistic wMDP in Figure 7(a), which results from running the test $T = \overline{up}_1.\overline{down}_4.\mathbf{0}$ in parallel with the system s_1 from the Introduction. Formally this is the sub-wMDP of the wMDP $(\overline{s_1} \parallel T)$ obtained by concentrating on the internal actions τ_w, which is just the wMDP represented by $(\overline{s_1} \parallel T) \backslash Act$ that we denote by $\overline{s_1} \parallel T$. Every time the experiment runs we get the initial benefit 3; three-quarters of the time we also get the benefit 7 while a quarter of time we get 5. So the total benefit is

$$3 + \frac{3}{4}\ 7 + \frac{1}{4}\ 5 = 9.5.$$

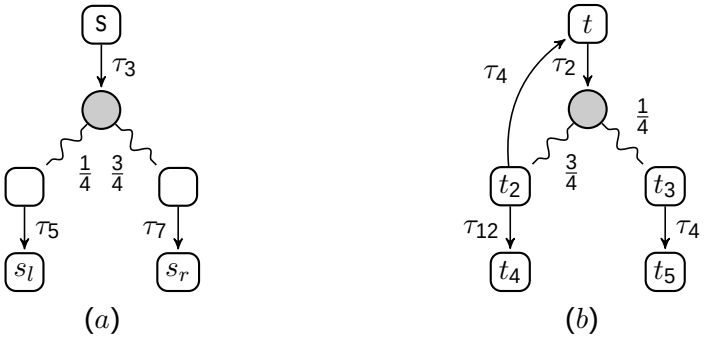

Figure 7: Testing systems

In the presence of nondeterminism there will in general be a set of possible bene ts, depending on the way in which the nondeterminism is resolved. Traditionally this resolution is expressed in terms of a scheduler, or adversary, which for each state decides which of its successors is chosen for execution, with the resulting set of bene ts consequently depending on the choice of scheduler. Here we take a more abstract approach, following [DvGHM09], and essentially allow arbitrary schedulers.

De nition 4.2 [Extreme derivatives] For any in a computation structure we write $=)_w$ if

$=^{\tau})_w$, that is is a hyper-derivative of

is *stable*, that is $s \bar{9}$ for every s in $d\ e$.

We say is an *extreme derivative* of , with weight w.

Intuitively every extreme derivation $=)_w$ represents a computation from the initial distribution guided by some implicit scheduler. For example, consider the hyper-derivation:

$$\begin{array}{rcl} & = & {}^{!}_{0} + {}_{0} \\ {}^{!}_{0} \ {}^{\tau}! {}_{w_0} & & {}^{!}_{1} + {}_{1} \\ & \vdots & \\ {}^{!}_{k} \ {}^{\tau}! {}_{w_k} & & {}^{!}_{k+1} + {}_{k+1} \\ & \vdots & \\ & = & \sum_{k=0} {}_{k} \end{array} \tag{7}$$

where $w = \sum_{k\ 0} w_k$. Initially, since ${}_0$ is stable, ${}^{!}_{0}$ contains (in its support) all states which can proceed with the computation. The implicit scheduler decides for each of these states which step to take, cumulating in the rst move, ${}^{!}_{0} \ {}^{\tau}! {}_{w_0} \ {}^{!}_{1} + {}_{1}$. At an arbitrary stage ${}^{!}_{k}$ contains all states which can continue; the scheduler decides which step to take for each individual state and the overall result of the schedulers decision for this stage is captured in the step ${}^{!}_{k} \ {}^{\tau}! {}_{w_k} \ {}^{!}_{k+1} + {}_{k+1}$.

Example 4.3 Referring to Figure 7(a) it is easy to see that $\bar{s}$ has a unique (degenerate) extreme derivative, $\overline{s_1} =) \ _{9.5} (\frac{1}{4}\overline{s_l} + \frac{3}{4}\overline{s_r})$, intuitively representing the unique weighted computation from $\overline{s_1}$. However, consider the wMDP in Figure 7(b), in which there is a nondeterministic choice from state t_2; here the extreme derivatives generated from $\bar{t}$, and their associated weights, will depend on the choices made during the computation by the implicit scheduler.

First suppose that the scheduler uses the static policy which maps t_2 to $h12, \overline{t_4}\, i$. Then it is easy to see that the generated extreme derivative, which is degenerate, is $\bar{t} =) \ _{12} (\frac{3}{4}\overline{t_4} + \frac{1}{4}\overline{t_5})$. However using the static policy which maps t_2 to $h4, \bar{t}\, i$ we generate, using (7), a non-degenerate extreme derivative; after some calculations this can be seen to be $\overline{t_1} =) \ _{24} \overline{t_5}$.

However there are many other possible implicit schedulers, for example at di erent times in the computations employing either of these static policies, or even choosing nondeterministically between them. But these are the only static policies and therefore we know from Theorem 2.20 that if $\overline{t_1} =) \ _w$ then w must take the form $p \ \ 12 + (1 \ \ p) \ \ 24$ for some $0 \ \ p \ \ 1$. That is the set of bene ts which can be generated from $\overline{t_1}$ is $f 24 \ \ 12 \ \ p \ j \ 0 \ \ p \ \ 1 g$.

De nition 4.4 In a wMDP, for any $\ 2 D(S)$, let

$$\text{Bene ts}(\ ) = f w 2 W \ j \ \ =) \ _w \ , \text{ for some } \ 2 D_{sub}(S) g.$$

Note that in general Bene ts( ) may contain 1, although by Theorem 2.27 this cannot be the case if the wMDP is bounded.

We compare Bene t sets as follows:

$$B_1 \ \ ^r_{\text{Ho}} B_2 \text{ if for every } r_1 2 B_1 \text{ there exists some } r_2 2 B_2 \text{ such that } r_1 \ \ r + r_2.$$

De nition 4.5 [May testing] For any two distributions , we write $\ v^r_{\text{may}}$ if for every nite (testing) process T, Bene ts($jj \ T$) $\ ^r_{\text{Ho}}$ Bene ts($jj \ T$). We write $\ v_{\text{may}}$ to mean that there is some $r 2 \text{R}_{\ 0}$ such that $\ v^r_{\text{may}}$.

This interpretation of processes is inherently optimistic; $\ v^r_{\text{may}}$ means that, given the investment r, every possible bene t produced by can in principle be improved upon by . Note that if we con ne ourselves to bounded wMDPs then by Theorem 2.27 and Theorem 2.30 no bene ts set used in this de nition will contain 1.

Our rst result shows that simulations can be used as a sound proof technique for this semantics. In order to prove that result, we need the following technical lemmas.

Lemma 4.6 Let , be two distributions in a bounded wMDP. Suppose $\ \overline{\text{C}}_r$ for some $r 2 \text{R}_{\ 0}$. If $\ =^{\tau}) \ _v \varepsilon$ then $\ =^{\tau}) \ _w \ ^{0}$ for some ^{0} such that $r + w \ \ v \ \ 0$.

Proof. If $\ =^{\tau}) \ _v \varepsilon$ then there is a sequence of τ transitions

$$^{\tau}\!I \ _{v_1} \ \ _1 \ \ ^{\tau}\!I \ _{v_2} \ \ _2 \ \ ^{\tau}\!I \ _{v_3}$$

such that $\sum_{k\ 1} v_k = v$. Since $\overline{\mathbb{C}}_r$, it can be shown by induction on i that there are weights w_i and subdistributions $_i$ with

$$=^{\tau}) \ (\sum_{1\le k\le i} w_k) \quad i$$
$$_i \ \overline{\mathbb{C}}_{(r+\sum_{1\le k\le i} w_k \quad \sum_{1\le k\le i} v_k)} \quad i$$

for all i 1. The compactness arguments in Appendix C (Corollary C.1) ensures that the set $f h\, w^{0},\ ^{0}\ i\ j \quad =^{\tau}) \ _{w'} \ ^{0} g$ is closed. As the sequence $f \sum_{1\ k\ i} w_k g_{i=1}^{1}$ has limit $\sum_{k\ 1} w_k$, there exists some subdistribution ^{0} such that $=^{\tau}) \ (\sum_{k\ge 1} w_k) \ ^{0}$. Since for each i 1, we have that $r + \sum_{1\ k\ i} w_k \quad \sum_{1\ k\ i} v_k$ 0. It follows that $r + \sum_{k\ 1} w_k \quad \sum_{k\ 1} v_k$ 0.

Lemma 4.7 Let , be two distributions in a bounded computation structure. If $\overline{\mathbb{C}}_r$ then Bene ts( ) $\overset{r}{\mathsf{Ho}}$ Bene ts( ).

Proof. For any v *2* Bene ts( ), there is some subdistribution ^{0} such that $=) \ _{v} \ ^{0}$. By Corollary 2.28 there is some subdistribution $^{0}_{\varepsilon}$ such that $=^{\tau}) \ _{v_1} \ (\ ^{0} + \ ^{0}_{\varepsilon})$, $j \ j = j \ ^{0} + \ ^{0}_{\varepsilon} j$, $^{0}_{\varepsilon} =^{\tau}) \ _{v_2} \ \varepsilon$ and $v_1 + v_2 = v$. By Corollary 3.8 there is some ^{00} such that $=^{\tau}) \ _{w_1} \ ^{00}$ and $(\ ^{0} + \ ^{0}_{\varepsilon}) \ \overline{\mathbb{C}}_{r+w_1 \quad v_1} \ ^{00}$. By Proposition 2.6 we can decompose ^{00} such that $^{00} = \ ^{0} + \ ^{0}_{\varepsilon}$, $^{0} \ \overline{\mathbb{C}}_{r_1} \ ^{0}$, $^{0}_{\varepsilon} \ \overline{\mathbb{C}}_{r_2} \ ^{0}_{\varepsilon}$, and

$$r_1 + r_2 = r + w_1 \quad v_1. \tag{8}$$

By Lemma 4.6 there is some $^{00}_{\varepsilon}$ such that $^{0}_{\varepsilon} =^{\tau}) \ _{w_2} \ ^{00}_{\varepsilon}$ and

$$r_2 + w_2 \quad v_2 \quad 0. \tag{9}$$

By the transitivity of hyper-derivations, Theorem 2.13, we obtain that $=^{\tau}) \ _{w_1+w_2} \ ^{0} + \ ^{00}_{\varepsilon}$. It follows that there is some extreme derivation $=) \ _{w} \ ^{000}$ for some w, ^{000} with

$$w \quad w_1 + w_2. \tag{10}$$

By (8), (9) and (10) we derive that

$$w \quad (r_1 + r_2 \quad r + v_1) + (v_2 \quad r_2) = v \quad r + r_1 \quad v \quad r.$$

Therefore, we have found some w *2* Bene ts( ) with $v \quad r + w$. Since this holds for any v *2* Bene ts( ), we have that Bene ts( ) $\overset{r}{\mathsf{Ho}}$ Bene ts( ).

Theorem 4.8 [Soundness] In a bounded wMDP, $P \ \overline{\mathbb{C}}_r \ Q$ implies $P \ \mathsf{v}^{r}_{\mathsf{may}} \ Q$.

Proof. For any nite test T, we can infer that

$$\begin{array}{ll} & P \ \overline{\mathbb{C}}_r \ Q \\ ) & (P \ jj \ T) \ \overline{\mathbb{C}}_r \ (Q \ jj \ T) \qquad \text{by Theorem 3.4} \\ ) & \text{Bene ts}(P \ jj \ T) \ \overset{r}{\mathsf{Ho}} \ \text{Bene ts}(Q \ jj \ T) \qquad \text{by Lemma 4.7} \\ , & P \ \mathsf{v}^{r}_{\mathsf{may}} \ Q \qquad \text{by de nition} \end{array}$$

In the next section we will see a partial converse to this result, in Corollary 4.13.

4.2 Success based testing

We follow our earlier approach [DvGHM09] of testing nondeterministic and probabilistic processes. A *test* is simply a process from the language CCMDP except that it may use special actions for reporting success. Thus we assume a countable set of fresh success actions not already in Act_τ; intuitively each ω in can be viewed as a particular way in which success can be achieved. We call CCMDP the language CCMDP extended with the new actions in . Its operational semantics is as in Figure 4 except that the rules (L-ALT) and (L-PAR) are modi ed as follows, where α ranges over Act_τ.

$$\frac{P_1 \xrightarrow{\alpha} {}_w\, Q \qquad P_2 \not\xrightarrow{\omega} \text{ for all } \omega \in}{P_1 + P_2 \xrightarrow{\alpha} {}_w\, Q} \quad \text{(l-alt1)}$$

$$\frac{P_1 \xrightarrow{\omega} {}_w\, Q \qquad P_2 \not\xrightarrow{\omega'} \text{ for all } \omega' \in \quad \{\omega\}}{P_1 + P_2 \xrightarrow{\omega} {}_w\, Q} \quad \text{(l-alt2)}$$

$$\frac{P_1 \xrightarrow{\alpha} {}_w\, Q \qquad P_2 \not\xrightarrow{\omega} \text{ for all } \omega \in}{P_1 \mid P_2 \xrightarrow{\alpha} {}_w\, Q \mid P_2} \quad \text{(l-par1)}$$

$$\frac{P_1 \xrightarrow{\omega} {}_w\, Q \qquad P_2 \not\xrightarrow{\omega'} \text{ for all } \omega' \in \quad \{\omega\}}{P_1 \mid P_2 \xrightarrow{\omega} {}_w\, Q \mid P_2} \quad \text{(l-par2)}$$

These rules guarantee that if a process P can report success via action ω, i.e. $P \xrightarrow{\omega} {}_w$ for some w and , then no other actions are enabled at P { neither a normal action in Act_τ nor another success action in is allowed. For this reason, we say that the wMDPs generated by the processes in CCMDP are ω-*respecting*.

De nition 4.9 Let $\in D_{sub}(S)$, we write Success( ) for the function (viewed as a vector) in $[0,1]$ such that Success( )(ω) = $\sum \{ (s) \mid s \in d\ e \text{ and } s \xrightarrow{\omega} \}$. We let

$$\text{Outcomes}( ) = \{\langle w, \text{Success}( ) \rangle \mid =) {}_w \text{ for some } \in D_{sub}(S)\}$$

Thus, intuitively, Outcomes( ) tabulates the rewards associated with vectors of successes, each particular vector obtained by an execution to completion of .

Let $B_1, B_2 \in \mathbb{R}_{\geq 0}$ [0,1] . We write $B_1 \sqsubseteq^{r}_{\mathrm{Ho}} B_2$ if for each $\langle r_1, f_1 \rangle \in B_1$ there exists some $\langle r_2, f_2 \rangle \in B_2$ such that $r_1 \leq r + r_2$ and $f_1(\omega) \leq f_2(\omega)$ for all $\omega \in$.

De nition 4.10 [Multi-success testing] For any two processes P, Q we write $P \sqsubseteq^{r}_{\mathrm{mmay}} Q$ if for every nite (testing) process T, Outcomes($P \parallel T$) $\sqsubseteq^{r}_{\mathrm{Ho}}$ Outcomes($Q \parallel T$).

Theorem 4.11 [Multi-success testing coincides with bene ts testing] For any $r \in \mathbb{R}_{\geq 0}$ and two processes P, Q whose operational semantics only give rise to bounded wMDPs,

$$P \sqsubseteq^{r}_{\mathrm{mmay}} Q \iff P \sqsubseteq^{r}_{\mathrm{may}} Q.$$

Proof. The general schema of the proof follows from [DvGMZ07] where it is shown that multi-success testing coincides with uni-success testing for nitary probabilistic automat.

We rst de ne the function Outcomes^{0} which is the same as Outcomes except that we allow any derivation instead of just extreme derivations.

$$\mathrm{Outcomes}^{0}(\mathcal{D}) = \{\langle w, \mathrm{Success}(\mathcal{D}') \mid \mathcal{D} \Longrightarrow_{w} \mathcal{D}' \text{ for some } \mathcal{D}' \in \mathcal{D}_{\mathrm{sub}}(S)\}$$

We claim that Outcomes^{0} satis es the next two properties.

1. For any $\mathcal{D} \in \mathcal{D}_{\mathrm{sub}}(S)$, we have $\mathrm{Outcomes}(\mathcal{D}) \sqsubseteq^{0}_{\mathrm{Ho}} \mathrm{Outcomes}^{0}(\mathcal{D})$ and also conversely $\mathrm{Outcomes}^{0}(\mathcal{D}) \sqsubseteq^{0}_{\mathrm{Ho}} \mathrm{Outcomes}(\mathcal{D})$.

2. For any $\mathcal{D} \in \mathcal{D}_{\mathrm{sub}}(S)$ in a bounded wMDP, the set $\mathrm{Outcomes}^{0}(\mathcal{D})$ is compact and convex.

For the rst claim, we observe that $\mathrm{Outcomes}(\mathcal{D}) \subseteq \mathrm{Outcomes}^{0}(\mathcal{D})$ from which it follows that $\mathrm{Outcomes}(\mathcal{D}) \sqsubseteq^{0}_{\mathrm{Ho}} \mathrm{Outcomes}^{0}(\mathcal{D})$. Since the wMDPs that we are considering are "ω-respecting", we have that if state s can enable a τ-action then $\mathrm{Success}(s) = \vec{0}$ where $\vec{0}$ is the empty vector with $\vec{0}(\omega) = 0$ for all $\omega \in \Omega$. It follows that $\mathcal{D} \Longrightarrow_{r} \mathcal{D}'$ implies $\mathrm{Success}(\mathcal{D}) \geq \mathrm{Success}(\mathcal{D}')$. So if $\mathcal{D} \Longrightarrow_{r_1} \mathcal{D}_1$ then $\mathcal{D} \Longrightarrow_{r_2} \mathcal{D}'$ for some extreme derivation $\mathcal{D}'$, i.e. $\mathcal{D} \Longrightarrow_{r_1 + r_2} \mathcal{D}'$, such that $\mathrm{Success}(\mathcal{D}_1) \geq \mathrm{Success}(\mathcal{D}')$. Hence, it is easy to show that $\mathrm{Outcomes}^{0}(\mathcal{D}) \sqsubseteq^{0}_{\mathrm{Ho}} \mathrm{Outcomes}(\mathcal{D})$.

For the second claim, we use the fact that the function Success is continuous. Let F_{Success} be the function given by

$$F_{\mathrm{Success}}(w, \mathcal{D}) = \langle w, \mathrm{Success}(\mathcal{D}) \rangle$$

which is also continuous. Again we appeal to the arguments in Appendix C (speci cally Corollary C.1) which guarantees that the set $\{\langle w, \mathcal{D}' \rangle \mid \mathcal{D} \Longrightarrow_{w} \mathcal{D}' \text{ for some } \mathcal{D}' \in \mathcal{D}_{\mathrm{sub}}(S)\}$ is compact and convex. Its image under F_{Success}, i.e. $\mathrm{Outcomes}^{0}(\mathcal{D})$, is also compact and easily seen to be convex.

With these two properties at hand, we are ready to prove that $P \sqsubseteq^{r}_{\mathrm{mmay}} Q \iff P \sqsubseteq^{r}_{\mathrm{may}} Q$. The only if direction is straightforward, so we focus on theif direction. We prove it by contradiction. Suppose that $P \sqsubseteq^{r}_{\mathrm{may}} Q$ but $P \not\sqsubseteq^{r}_{\mathrm{mmay}} Q$. Then there is some multi-success test T such that

Lemma B.12 Suppose $\bar{s} = \tau)_w \quad {}^0$ with $hw, \quad {}^0 i = \sum_{i=0}^{1} hw_i, \quad {}_i \; i$ for some properly related $\quad {}_i$ and some w_i with $w_0 = 0$. Let $f\delta_j g_{j=0}^{1}$ be a nondecreasing sequence of discount factors converging to 1. Then for any weight function w it holds that

$$\mathrm{w} \quad hw, \quad {}^0 i \;=\; \lim_{j\,!\,1} \sum_{i=0}^{1} (\delta_j)^i (\mathrm{w} \quad hw_i, \quad {}_i \; i).$$

Proof. We have three cases. If $w = 1$ and $\mathrm{w}(s_0) > 0$, then it is easy to see that both sides of the equation are equal to 1. Similarly, if $w = 1$ and $\mathrm{w}(s_0) < 0$, both sides are equal to 1. Otherwise, $j\mathrm{w} \quad hw, \quad {}^0 ij < 1$ and we proceed as follows.

Let $f : \mathrm{N} \quad \mathrm{N} \; ! \; \mathrm{R}$ be the function de ned by $f(i,j) = (\delta_j)^i (\mathrm{w} \quad hw_i, \quad {}_i \; i)$. We check that f satis es the four conditions in Proposition D.2.

1. f satis es condition C1. For all $i, j_1, j_2 \; 2$ N, if $j_1 \quad j_2$ then $(\delta_{j_1})^i \quad (\delta_{j_2})^i$. It follows that

$$jf(i,j_1)j \;=\; j(\delta_{j_1})^i (\mathrm{w} \quad hw_i, \quad {}_i \; i)j \qquad j(\delta_{j_2})^i (\mathrm{w} \quad hw_i, \quad {}_i \; i)j \;=\; jf(i,j_2)j.$$

2. f satis es condition C2. For any $i \; 2$ N, we have

$$\lim_{j\,!\,1} jf(i,j)j \;=\; \lim_{j\,!\,1} j(\delta_j)^i (\mathrm{w} \quad hw_i, \quad {}_i \; i)j \;=\; j\mathrm{w} \quad hw_i, \quad {}_i \; ij. \tag{30}$$

3. f satis es condition C3. For any $n \; 2$ N, the partial sum $S_n = \sum_{i=0}^{n} \lim_{j\,!\,1} jf(i,j)j$ is bounded because

$$\begin{aligned} & \sum_{i=0}^{n} \lim_{j\,!\,1} jf(i,j)j \\ = \; & \sum_{i=0}^{n} j\mathrm{w} \quad hw_i, \quad {}_i \; ij \\ & \sum_{i=0}^{1} j\mathrm{w} \quad hw_i, \quad {}_i \; ij \\ & \sum_{i=0}^{1} (w_i + j \quad {}_i \; j) \\ = \; & w + j \quad {}^0 j \end{aligned}$$

where the rst equality is justi ed by (30).

4. f satis es condition C4. For any $i, j_1, j_2 \; 2$ N, if $j_1 \quad j_2$ then

$$\begin{aligned} & f(i,j_1) + jf(i,j_1)j \\ = \; & (\delta_{j_1})^i (\mathrm{w} \quad hw_i, \quad {}_i \; i) + j(\delta_{j_1})^i (\mathrm{w} \quad hw_i, \quad {}_i \; i)j \\ = \; & (\delta_{j_1})^i (\mathrm{w} \quad hw_i, \quad {}_i \; i + j\mathrm{w} \quad hw_i, \quad {}_i \; ij) \\ & (\delta_{j_2})^i (\mathrm{w} \quad hw_i, \quad {}_i \; i + j\mathrm{w} \quad hw_i, \quad {}_i \; ij) \\ = \; & f(i,j_2) + jf(i,j_2)j. \end{aligned}$$

Therefore, we can use Proposition D.2 to do the following inference.

$$\begin{aligned} & \lim_{j\,!\,1} \sum_{i=0}^{1} (\delta_j)^i (\mathrm{w} \quad hw_i, \quad {}_i \; i) \\ = \; & \sum_{i=0}^{1} \lim_{j\,!\,1} (\delta_j)^i (\mathrm{w} \quad hw_i, \quad {}_i \; i) \\ = \; & \sum_{i=0}^{1} \mathrm{w} \quad hw_i, \quad {}_i \; i \\ = \; & \mathrm{w} \quad \sum_{i=0}^{1} hw_i, \quad {}_i \; i \\ = \; & \mathrm{w} \quad hw, \quad {}^0 i \end{aligned}$$

Corollary B.13 Let $\{\delta_j\}_{j=0}^{\infty}$ be a nondecreasing sequence of discount factors converging to 1. For any static policy π and weight function w, it holds that $P^{1,\pi,w} = \lim_{j \to 1} P^{\delta_j,\pi,w}$.

Proof. We need to show that $P^{1,\pi,w}(s) = \lim_{j \to 1} P^{\delta_j,\pi,w}(s)$, for any state s. Note that for any discount δ_j, each state s enables a unique discounted hyper-SP-derivation $\bar{s} \rightsquigarrow^{\tau}_{\delta_j,\pi,w^j} \rho^j$ such that $\langle w^j, \rho^j \rangle = \sum_{i=0}^{\infty} (\delta_j)^i \langle w_i, \rho_i \rangle$ for some properly related ρ_i and some w_i with $w_0 = 0$. Let $w = \sum_{i=0}^{\infty} w_i$ and $\rho' = \sum_{i=0}^{\infty} \rho_i$. We have $\bar{s} \rightsquigarrow^{\tau}_{1,\pi,w} \rho'$. Then we can infer that

$$\begin{aligned}
& \lim_{j \to 1} P^{\delta_j,\pi,w}(s) \\
= \; & \lim_{j \to 1} w \langle w^j, \rho^j \rangle \\
= \; & \lim_{j \to 1} w \sum_{i=0}^{\infty} (\delta_j)^i \langle w_i, \rho_i \rangle \\
= \; & \lim_{j \to 1} \sum_{i=0}^{\infty} (\delta_j)^i (w \langle w_i, \rho_i \rangle) \\
= \; & w \langle w, \rho' \rangle \quad \text{by Lemma B.12} \\
= \; & P^{1,\pi,w}(s)
\end{aligned}$$

Theorem B.14 (Theorem 2.19) In a finitary wMDP, for any weight function w there exists a static policy π such that $P^{1,w}_{\max} = P^{1,\pi,w}$.

Proof. Let w be a weight function. By Lemma B.4 and Proposition B.10, for every discount factor $\delta < 1$ there exists a max-seeking static policy with respect to δ and w such that

$$P^{\delta,w}_{\max} = P^{\delta,\pi,w}. \tag{31}$$

Since the wMDP is finitary, there are finitely many different static policies. There must exist a static policy π such that (31) holds for in finitely many discount factors. In other words, for every nondecreasing sequence $\{\delta_n\}_{n=0}^{\infty}$ converging to 1, with $\delta_n < 1$ for all $n \geq 0$, there exists a sub-sequence $\{\delta_{n_j}\}_{j=0}^{\infty}$ converging to 1 and a static policy $\pi^\star$ such that

$$P^{\delta_{n_j},w}_{\max} = P^{\delta_{n_j},\pi^?,w} \quad \text{for all } j \geq 0. \tag{32}$$

For any state s, we infer as follows.

$$\begin{aligned}
& P^{1,w}_{\max}(s) \\
= \; & \sup\{w \langle w, \rho' \rangle \mid \bar{s} \rightsquigarrow^{\tau}_{w} \rho'\} \\
= \; & \sup\{\lim_{j \to 1} \sum_{i=0}^{\infty} (\delta_{n_j})^i (w \langle w_i, \rho_i \rangle) \mid \bar{s} \rightsquigarrow^{\tau}_{w} \rho' \text{ with } \langle w, \rho' \rangle = \textstyle\sum_{i=0}^{\infty} \langle w_i, \rho_i \rangle\} \\
& \quad \text{[by Lemma B.12]} \\
& \lim_{j \to 1} \sup\{\textstyle\sum_{i=0}^{\infty} (\delta_{n_j})^i (w \langle w_i, \rho_i \rangle) \mid \bar{s} \rightsquigarrow^{\tau}_{w} \rho' \text{ with } \langle w, \rho' \rangle = \sum_{i=0}^{\infty} \langle w_i, \rho_i \rangle\} \\
= \; & \lim_{j \to 1} \sup\{w \textstyle\sum_{i=0}^{\infty} (\delta_{n_j})^i \langle w_i, \rho_i \rangle \mid \bar{s} \rightsquigarrow^{\tau}_{w} \rho' \text{ with } \langle w, \rho' \rangle = \sum_{i=0}^{\infty} \langle w_i, \rho_i \rangle\} \\
= \; & \lim_{j \to 1} \sup\{w \langle w'', \rho'' \rangle \mid \bar{s} \rightsquigarrow^{\tau}_{\delta_{n_j},w'} \rho''\} \\
= \; & \lim_{j \to 1} P^{\delta_{n_j},w}_{\max}(s) \\
= \; & \lim_{j \to 1} P^{\delta_{n_j},\pi^?,w}(s) \quad \text{[by (32)]} \\
= \; & P^{1,\pi^?,w}(s) \quad \text{[by Corollary B.13]}
\end{aligned}$$

The other direction, $P^{1,w}_{\max}(s) \geq P^{1,\pi^?,w}(s)$, is trivial in view of Definitions B.2 and B.8.

C Compactness arguments

In this appendix we give the detailed proofs of the two results from Section 3.2, Proposition 3.10 and Proposition 3.12 which rely on compactness arguments.

Corollary C.1 Let be a subdistribution in a bounded wMDP. The set $fhw, \ ^0 i \ j \ =^{\tau})_w \ ^0 g$ is compact and convex.

Proof. Let $\mathrm{pp}_1, ..., \mathrm{pp}_n$ $(n \quad 1)$ be all the static policies in the bounded wMDP. Each policy determines a hyper-SP-derivation $=^{\tau})_{\mathrm{pp}_i, w_i} \ ^0_i$. By Theorem 2.27, the weight w_i is nite. Let C be the convex closure of $fhw_i, \ _i i \ j \ 1 \quad i \quad ng$. Let D be the set $fhw, \ ^0 i \ j \ =^{\tau})_w \ ^0 g$. By Theorem 2.20 we have $D \quad C$. On the other hand, it is easy to see from Lemma 2.11(1) that D is convex and thus $C \quad D$. Consequently, D coincides with C, the convex closure of a nite set. Therefore, it is Cauchy closed and bounded, thus being compact.

In order to extend the above result to the relation $=^{\alpha})$, for any α 2 Act, we need some preliminary concepts.

De nition C.2 A subset D R $D_{sub}(S)$ is said to be *nitely generable* whenever there is some nite set F R $D_{sub}(S)$ such that $D = lF$. Then a relation $R \quad X$ R $D_{sub}(S)$ is said to be *nitely generable* if for every x in X the set $x \ R$ is nitely generable.

Lemma C.3 If a set is nitely generable, then it is compact and convex.

Proof. A direct consequence of the de nition of nite generability.

De nition C.4 Let $R_1, R_2 2 \ D_{sub}(S)$ (R $D_{sub}(S)$) be two relations. We de ne their composition $R_1; R_2$ by letting $R_1; R_2 \ hw, \quad i$ if there are some $w_1, w_2, \ ^0$ such that $R_1 \ hw_1, \ ^0 i$ and $^0 R_2 \ hw_2, \quad i$ with $w_1 + w_2 = w$.

Lemma C.5 Let $R_1, R_2 \quad D_{sub}(S)$ (R $D_{sub}(S)$) be nitely generable. Moreover, R_2 is both linear and decomposable. Then the relation $R_1; R_2$ is nitely generable.

Proof. Let B^i be a nite set of pairs of reals and subdistributions such that $R_i = lB^i$ for $i = 1, 2$. By exploiting the linearity and decomposability of R_2, we can check that

$$R_1; R_2 \quad = \quad l \ [\ f \ hw, \varepsilon \ i + B^2 \ \ j \ hw, \quad i \ 2 \ B^1 \ g.$$

where $hw, \varepsilon \ i + B^2$ stands for the set $fhw, \varepsilon \ i + hv, \quad i \ j \ hv, \quad i \ 2 \ B^2 \ g$.

We are now ready to establish Proposition 3.10; it follows from this slightly more general result:

Lemma C.6 Let be a subdistribution in a bounded wMDP. The set $fhw, \ ^0 i \ j \ =^{\alpha})_w \ ^0 g$ is compact and convex.

Proof. The relation $=^{\alpha})$ is a composition of three stages: $=^{\tau})$; $^{\alpha}!$; $=^{\tau})$. In the proof of Corollary C.1 we have shown that $=^{\tau})$ is nitely generable. Since a bounded wMDP is nitary, the relation $^{\alpha}!$ is also nitely generable. We observe that $^{\alpha}!$ is both linear and decomposable, so is $=^{\tau})$ by Lemma 2.11. It follows from Proposition C.5 that $=^{\alpha})$ is nitely generable. By Lemma C.3 we have that $=^{\alpha})$ is compact and convex.

Corollary C.7 In a bounded wMDP, the relation $=\!\!\stackrel{\alpha}{)}$ is the lifting of the compact and convex relation $=\!\!\stackrel{\alpha}{)}_S$, where $s =\!\!\stackrel{\alpha}{)}_S$ means $\overline{s} =\!\!\stackrel{\alpha}{)}$.

Proof. The relation $=\!\!\stackrel{\alpha}{)}_S$ is $=\!\!\stackrel{\alpha}{)}$ restricted to point distributions. We have shown that $=\!\!\stackrel{\alpha}{)}$ is compact and convex in Lemma C.6. Therefore, $=\!\!\stackrel{\alpha}{)}_S$ is compact and convex. Its lifting coincides with $=\!\!\stackrel{\alpha}{)}$, which follows from Proposition 2.11.

Our next step is to show that each of the relations C^k is closed. This requires some results to be first established.

Lemma C.8 If $R \subseteq S \times (\mathbb{R}_{>0} \to D_{sub}(S))$ is compact, then so is its set of choice functions $\mathsf{Ch}(R)$.

Proof. Suppose that R is compact, that is closed and bounded. It is straightforward to show that $\mathsf{Ch}(R)$, under the metric defined on page 22, is therefore also closed and bounded. It follows that $\mathsf{Ch}(R)$ forms a complete metric space. Moreover, since R is bounded, $\mathsf{Ch}(R)$ is also totally bounded. Therefore, $\mathsf{Ch}(R)$ is compact, for a metric space is compact if and only if it is complete and totally bounded.

Let $\beta(x)$ be a predicate with variable x ranging over some set X. We use the notation $\beta(\ )$ to represent the set $\{x \in X \mid \beta(x)\}$.

Lemma C.9 Suppose there is a continuous function $g : \mathbb{R}^2_{>0} \to \mathbb{R}$ and two convex relations $R_1, R_2 \subseteq S \times (\mathbb{R}_{>0} \to D_{sub}(S))$ such that R_1 is compact and R_2 is closed. Then the set

$$Z = \{\langle r, \ \rangle \mid r \in \mathbb{R}_{>0} \text{ and } \exists w \in \mathbb{R}_{>0} : (\ \overline{R_1}\langle w, \ \rangle) \setminus (\ \overline{R_2}\langle g(r,w), \ \rangle) \neq \emptyset\}$$

is closed.

Proof. We will use the continuous function E, defined in the proof of Theorem 3.14; recall that it also maps closed sets to closed sets.

Let $r, w \in \mathbb{R}_{>0}$, $\ \in D_{sub}(S)$, and $f \in S \to \mathbb{R}_{>0} \to D_{sub}(S)$. Then define the following four functions

$$\begin{aligned} H_1 &: \langle\langle r, \ \rangle, f \rangle \mapsto \langle r, \langle \ , f \rangle\rangle \\ H_2 &: \langle r, \langle w, \ \rangle\rangle \mapsto \langle\langle r, w\rangle, \ \rangle \\ F_E &: \langle r, \langle \ , f \rangle\rangle \mapsto \langle r, E(\ , f)\rangle \\ G_g &: \langle\langle r, w\rangle, \ \rangle \mapsto \langle g(r,w), \ \rangle \end{aligned}$$

which are continuous. Finally let

$$Z' = \pi_1(H_1^{-1} \circ F_E^{-1} \circ H_2^{-1} \circ G_g^{-1} \circ E(f \times g \times \mathsf{Ch}(R_2)) \setminus (\mathbb{R}_{>0} \to D_{sub}(S)) \times \mathsf{Ch}(R_1))$$

where $\pi_1 : (\mathbb{R}_{>0} \to D_{sub}(S)) \times \mathsf{Ch}(R_1) \to \mathbb{R}_{>0} \to D_{sub}(S)$ is the projection onto the first component of a pair. Since R_2 is closed, it easily follows that $\mathsf{Ch}(R_2)$ is also closed. Then the product $f \times g \times \mathsf{Ch}(R_2)$ is closed. Its image under the closed function E is also closed. Since the four functions G_g, H_2, F_E, H_1 are continuous and the inverse image of a closed set is closed, we know that $H_1^{-1} \circ F_E^{-1} \circ H_2^{-1} \circ G_g^{-1} \circ E(f \times g \times \mathsf{Ch}(R_2))$ is closed. On the other hand, since R_1 is compact, by Lemma C.8 the set of choice functions $\mathsf{Ch}(R_1)$ is compact. It is then easy to see that $(\mathbb{R}_{>0} \to D_{sub}(S)) \times \mathsf{Ch}(R_1)$ is closed. It follows that the intersection of two closed sets

$$H_1^{-1} \circ F_E^{-1} \circ H_2^{-1} \circ G_g^{-1} \circ E(f \times g \times \mathsf{Ch}(R_2)) \setminus (\mathbb{R}_{>0} \to D_{sub}(S)) \times \mathsf{Ch}(R_1)$$

is closed. By the tube lemma in topology theory, the projection π_1 is closed[1]. Therefore, we have that Z^0 is closed.

We now show that $Z = Z^0$.

$\langle r, \quad \rangle \in Z^0$
$\Leftrightarrow$ $\langle\langle r, \quad \rangle, f_1 \rangle \in H_1^{-1} \quad F_E^{-1} \quad H_2^{-1} \quad G_g^{-1} \quad E(f \quad g \quad \mathsf{Ch}(R_2))$ for some $f_1 \in \mathsf{Ch}(R_1)$
$\Leftrightarrow$ $\langle r, \langle \quad, f_1 \rangle \rangle \in F_E^{-1} \quad H_2^{-1} \quad G_g^{-1} \quad E(f \quad g \quad \mathsf{Ch}(R_2))$ for some $f_1 \in \mathsf{Ch}(R_1)$
$\Leftrightarrow$ $\langle r, E(\quad, f_1) \rangle \in H_2^{-1} \quad G_g^{-1} \quad E(f \quad g \quad \mathsf{Ch}(R_2))$ for some $f_1 \in \mathsf{Ch}(R_1)$
$\Leftrightarrow$ $\langle r, \mathsf{Exp} \quad (f_1) \rangle \in H_2^{-1} \quad G_g^{-1} \quad E(f \quad g \quad \mathsf{Ch}(R_2))$ for some $f_1 \in \mathsf{Ch}(R_1)$
$\Leftrightarrow$ $\overline{R_1}\langle w, \quad ^0 \rangle$ and $\langle r, \langle w, \quad ^0 \rangle \rangle \in H_2^{-1} \quad G_g^{-1} \quad E(f \quad g \quad \mathsf{Ch}(R_2))$ for some $\langle w, \quad ^0 \rangle$
$\Leftrightarrow$ $\overline{R_1}\langle w, \quad ^0 \rangle$ and $\langle\langle r, w \rangle, \quad ^0 \rangle \in G_g^{-1} \quad E(f \quad g \quad \mathsf{Ch}(R_2)$ for some $\langle w, \quad ^0 \rangle$
$\Leftrightarrow$ $\overline{R_1}\langle w, \quad ^0 \rangle$ and $\langle g(r, w), \quad ^0 \rangle \in E(f \quad g \quad \mathsf{Ch}(R_2)$ for some $\langle w, \quad ^0 \rangle$
$\Leftrightarrow$ $\overline{R_1}\langle w, \quad ^0 \rangle$ and $\overline{R_2}\langle g(r, w), \quad ^0 \rangle$ for some $\langle w, \quad ^0 \rangle$
$\Leftrightarrow$ $(\overline{R_1}\langle w, \quad \rangle) \cap (\overline{R_2}\langle g(r, w), \quad \rangle) \neq \emptyset$ for some w
$\Leftrightarrow$ $\langle r, \quad \rangle \in Z$.

This lemma enables us to establish the second requirement of the appendix:

Proposition C.10 [Proposition 3.12] In a bounded wMDP, for every $k \in \mathbb{N}$, the relation C^k is closed and convex.

Proof. By induction on k. For $k = 0$ the result is obvious. So let us assume that C^k is closed and convex. We have to show that

$$s \quad \mathsf{C}^{(k+1)} \text{ is closed and convex, for every state } s \tag{33}$$

For every $\alpha, v, \quad$ let

$$G_{\alpha,v, \quad} = \{\langle r, \quad \rangle \mid r \in \mathbb{R}_{\geq 0} \text{ and } \exists w \in \mathbb{R}_{\geq 0} : (\quad =^{\alpha}) \quad w) \cap (\quad \overline{\mathsf{C}^k}_{r+w \quad v}) \neq \emptyset\}.$$

By Corollary C.7, the relation $=^{\alpha})$ is lifted from a compact and convex relation. By induction hypothesis we know that C^k is closed and convex. The function $g : \mathbb{R}^2_{\geq 0} \to \mathbb{R}_{\geq 0}$ given by $g(r, w) = r + w \quad v$ is continuous. So we can appeal to Lemma C.9 and conclude that each $G_{\alpha,v, \quad}$ is closed. By De nition 2.2 it is also easy to see that $G_{\alpha,v, \quad}$ is convex. But it follows that $s \quad \mathsf{C}^{(k+1)}$ is also closed and convex as it can be written as

$$\bigcap \{G_{\alpha,v, \quad} \mid s \quad ^{\alpha}\!\!\to v \quad \}.$$

[1] In general, the projection $_1 : X \quad Y \to X$ is not closed. For example, if $X = Y = \mathbb{R}$, then $_1$ maps the closed set $\{\langle x; y \rangle \in \mathbb{R}^2 \mid xy = 1\}$ into $\mathbb{R} \setminus \{0\}$ which is not closed. However, the tube lemma tells us that if X is any topological space and Y a compact space, then the projection map $_1$ is closed.

D Bounded continuity

In this section we study the property of bounded continuity of real-valued binary functions, which plays a crucial role in the proof of Lemma B.12. We first consider nonnegative functions.

Proposition D.1 [Bounded continuity - nonnegative function] Given a function $f : \mathbb{N} \times \mathbb{N} \to \mathbb{R}_{\geq 0}$ which satisfies the following conditions

- **C1.** f is monotonic on the second parameter, i.e. $j_1 \leq j_2$ implies $f(i, j_1) \leq f(i, j_2)$ for all $i, j_1, j_2 \in \mathbb{N}$.
- **C2.** For any $i \in \mathbb{N}$, the limit $\lim_{j \to \infty} f(i, j)$ exists.
- **C3.** For any $n \in \mathbb{N}$, the partial sum $S_n = \sum_{i=0}^{n} \lim_{j \to \infty} f(i, j)$ is bounded, i.e. there exists some $c \in \mathbb{R}_{\geq 0}$ such that $S_n \leq c$ for all $n \geq 0$.

then it holds that

$$\sum_{i=0}^{\infty} \lim_{j \to \infty} f(i, j) = \lim_{j \to \infty} \sum_{i=0}^{\infty} f(i, j).$$

Proof. Let ϵ be any positive real number. By C3 the sequence $\{S_n\}_{n=0}^{\infty}$ is bounded and it is nondecreasing, so it converges to $\sum_{i=0}^{\infty} \lim_{j \to \infty} f(i, j)$. Then there exists some $n_\epsilon \in \mathbb{N}$ such that

$$0 \leq \sum_{i=0}^{\infty} \lim_{j \to \infty} f(i, j) - \sum_{i=0}^{n_\epsilon} \lim_{j \to \infty} f(i, j) \leq \frac{\epsilon}{2}. \tag{34}$$

By C1 and C2, for any $i \in \mathbb{N}$, the sequence $\{f(i, j)\}_{j=0}^{\infty}$ is nondecreasing and converges to $\lim_{j \to \infty} f(i, j)$. Therefore, for each $i \in \mathbb{N}$, there exists some $m_{i,\epsilon,n} \in \mathbb{N}$ such that

$$\forall j \geq m_{i,\epsilon,n} : \quad 0 \leq \lim_{j' \to \infty} f(i, j') - f(i, j) \leq \frac{\epsilon}{2(n_\epsilon + 1)}. \tag{35}$$

Let $m_\epsilon = \max\{m_{i,\epsilon,n} \mid 0 \leq i \leq n_\epsilon\}$. It follows from (35) that

$$\forall j \geq m_\epsilon : \quad 0 \leq \sum_{i=0}^{n_\epsilon} \lim_{j' \to \infty} f(i, j') - \sum_{i=0}^{n_\epsilon} f(i, j) \leq \frac{\epsilon}{2}. \tag{36}$$

By summing up (34) and (36), we obtain

$$\forall j \geq m_\epsilon : \quad 0 \leq \sum_{i=0}^{\infty} \lim_{j' \to \infty} f(i, j') - \sum_{i=0}^{n_\epsilon} f(i, j) \leq \epsilon. \tag{37}$$

By C1 and C2, we have that $f(i, j) \leq \lim_{j' \to \infty} f(i, j')$ for any $i, j \in \mathbb{N}$. So for any $j, n \in \mathbb{N}$ the partial sum $\sum_{i=0}^{n} f(i, j)$ is bounded as

$$\sum_{i=0}^{n} f(i, j) \leq \sum_{i=0}^{n} \lim_{j' \to \infty} f(i, j') \leq c$$

according to C3. Thus it converges to $\sum_{i=0}^{\infty} f(i,j)$. Then for any $j \in \mathbb{N}$ there exists some $n_{j,\epsilon}$ such that

$$\forall n \quad n_{j,\epsilon}: \qquad 0 \qquad \sum_{i=0}^{\infty} f(i,j) \qquad \sum_{i=0}^{n} f(i,j) \qquad \epsilon. \tag{38}$$

Now consider the particular case that $j = m_\epsilon$. Let $N_\epsilon = \max\{n_\epsilon, n_{m_\epsilon,\epsilon}\}$. We know from (37)

$$0 \qquad \sum_{i=0}^{\infty} \lim_{j \to \infty} f(i,j) \qquad \sum_{i=0}^{N} f(i,m_\epsilon) \qquad \epsilon. \tag{39}$$

From (38) we infer that

$$\epsilon \qquad \sum_{i=0}^{N} f(i,m_\epsilon) \qquad \sum_{i=0}^{\infty} f(i,m_\epsilon) \qquad 0. \tag{40}$$

By summing up (39) and (40), we derive that

$$\epsilon \qquad \sum_{i=0}^{\infty} \lim_{j \to \infty} f(i,j) \qquad \sum_{i=0}^{\infty} f(i,m_\epsilon) \qquad \epsilon. \tag{41}$$

We conclude from (41) that

$$\lim_{j \to \infty} \sum_{i=0}^{\infty} f(i,j) \;=\; \sum_{i=0}^{\infty} \lim_{j \to \infty} f(i,j).$$

Proposition D.2 [Bounded continuity - general function] Given a function $f : \mathbb{N} \times \mathbb{N} \to \mathbb{R}$ which satisfies the following conditions

C1. For all $i, j_1, j_2 \in \mathbb{N}$, we have $j_1 \le j_2$ implies $|f(i,j_1)| \le |f(i,j_2)|$.

C2. For any $i \in \mathbb{N}$, the limit $\lim_{j \to \infty} |f(i,j)|$ exists.

C3. For any $n \in \mathbb{N}$, the partial sum $S_n = \sum_{i=0}^{n} \lim_{j \to \infty} |f(i,j)|$ is bounded, i.e. there exists some $c \in \mathbb{R}_0$ such that $S_n \le c$ for all $n \ge 0$.

C4. For all $i, j_1, j_2 \in \mathbb{N}$, we have $j_1 \le j_2$ implies $f(i,j_1) + |f(i,j_1)| \le f(i,j_2) + |f(i,j_2)|$.

then it holds that

$$\sum_{i=0}^{\infty} \lim_{j \to \infty} f(i,j) \;=\; \lim_{j \to \infty} \sum_{i=0}^{\infty} f(i,j).$$

Proof. For any $i, j \in \mathbb{N}$, we have $f(i,j) + |f(i,j)| \ge 2|f(i,j)| \ge 2 \lim_{j \to \infty} |f(i,j)|$ by C1 and C2. Therefore, for any $i \in \mathbb{N}$, the sequence $\{f(i,j) + |f(i,j)|\}_{j=0}^{\infty}$ has a limit. That is, we have the condition

C5. for any $i \in \mathbb{N}$, the limit $\lim_{j \to \infty} (f(i,j) + |f(i,j)|)$ exists.

Moreover, it holds that $\lim_{j\,!\,1}(f(i,j) + jf(i,j)j) \quad 2 \lim_{j\,!\,1} jf(i,j)j$. It follows that

C6. for any n 2 N, the partial sum $\sum_{i=0}^{n} \lim_{j\,!\,1}(f(i,j) + jf(i,j)j) \quad 2 \sum_{i=0}^{n} \lim_{j\,!\,1} jf(i,j)j$ $2c$.

By Proposition D.1 and conditions C1, C2 and C3, we infer that

$$\lim_{j\,!\,1} \sum_{i=0}^{1} jf(i,j)j = \sum_{i=0}^{1} \lim_{j\,!\,1} jf(i,j)j. \tag{42}$$

By Proposition D.1 and conditions C4, C5 and C6, we infer that

$$\lim_{j\,!\,1} \sum_{i=0}^{1} (f(i,j) + jf(i,j)j) = \sum_{i=0}^{1} \lim_{j\,!\,1} (f(i,j) + jf(i,j)j). \tag{43}$$

Since $\sum_{i=0}^{1} f(i,j) = \sum_{i=0}^{1}(f(i,j) + jf(i,j)j) \quad \sum_{i=0}^{1} jf(i,j)j$, we then have

$$\begin{aligned}
\lim_{j\,!\,1} \sum_{i=0}^{1} f(i,j) &= \lim_{j\,!\,1} \Big(\sum_{i=0}^{1}(f(i,j) + jf(i,j)j) \quad \sum_{i=0}^{1} jf(i,j)j \Big) \\
&\quad \text{[existence of the two limits by (42) and (43)]} \\
&= \lim_{j\,!\,1} \sum_{i=0}^{1}(f(i,j) + jf(i,j)j) \quad \lim_{j\,!\,1} \sum_{i=0}^{1} jf(i,j)j \\
&\quad \text{[by (42) and (43)]} \\
&= \sum_{i=0}^{1} \lim_{j\,!\,1}(f(i,j) + jf(i,j)j) \quad \sum_{i=0}^{1} \lim_{j\,!\,1} jf(i,j)j \\
&= \sum_{i=0}^{1} (\lim_{j\,!\,1}(f(i,j) + jf(i,j)j) \quad \lim_{j\,!\,1} jf(i,j)j) \\
&= \sum_{i=0}^{1} \lim_{j\,!\,1}(f(i,j) + jf(i,j)j \quad jf(i,j)j) \\
&= \sum_{i=0}^{1} \lim_{j\,!\,1} f(i,j)
\end{aligned}$$

E Completeness for bene ts testing

Here we outline the details for the proof of Theorem 4.12, which underlies the completeness of bene ts testing for amortised weighted simulation. They are a variation on the proof of the corresponding result in [DvGHM09].

Lemma E.1 Let be a distribution and T, T_i be tests.

1. o 2 Outcomes($jj\,\omega$) i $o = h0, \vec{\omega}\,i$.
2. o 2 Outcomes($jj\,a_0.T$) and o 6 $\vec{0}$ i $\overset{a}{=})_w$ ^{0} and $o = o^0 + hw, \vec{0}\,i$ for some o^0 2 Outcomes($^0\,jj\,T$).
3. o 2 Outcomes($jj\,T_1\,{}_p\,T_2$) i $o = p_i\,o_1 + (1 \quad p)\,o_2$ for some o_i 2 Outcomes($jj\,T_i$).
4. o 2 Outcomes($jj\,(\tau_0.T_1 + \tau_0.T_2)$) if there are q 2 $[0,1]$, weight w and distributions $_1$, $_2$ such that $\overset{\tau}{=})_w\,q \quad {}_1 + (1 \quad q) \quad {}_2$ and $o = q\,o_1 + (1 \quad q)\,o_2 + hw, \vec{0}\,i$ for certain o_i 2 Outcomes($_i\,jj\,T_i$).

Proof.

1. The states in the support of $\mathit{jj}\,\omega$ has a unique outgoing transition labelled by ω. Therefore, $\mathit{jj}\,\omega$ is the unique extreme derivative of itself. As Success($\mathit{jj}\,\omega$) = $\vec{\omega}$, we have Outcomes($\mathit{jj}\,\omega$) = $\{\langle 0, \vec{\omega}\rangle\}$.

2. ($\Rightarrow$) Suppose $\xrightarrow{a}_w$ μ, $o' \in$ Outcomes($\mu \mathit{jj} T$) and $o = o' + \langle w, \vec{0}\rangle$. With loss of generality we may assume that $\xRightarrow{\tau}_{w_1} \mu_1 \xrightarrow{a}_{w_2} \mu_2 \xRightarrow{\tau}_{w_3} \mu'$ with $w = w_1 + w_2 + w_3$. Using Lemma 3.3, we have that $\mathit{jj}\, a_0.T \xRightarrow{\tau}_{w_1} \mu_1 \mathit{jj}\, a_0.T \xrightarrow{a}_{w_2} \mu_2 \mathit{jj}\, T \xRightarrow{\tau}_{w_3} \mu' \mathit{jj}\, T$. It follows that $o \in$ Outcomes($\mathit{jj}\, a_0.T$).

   ($\Leftarrow$) Suppose $o \in$ Outcomes($\mathit{jj}\, a_0.T$) and $o \neq \vec{0}$. Then there must be a μ' such that $\xRightarrow{\tau}_{w_1} \xrightarrow{a}_{w_2} \mu'$ and some $o' \in$ Outcomes($\mu' \mathit{jj}\, T$) exists with $o = o' + \langle w_1 + w_2, \vec{0}\rangle$.

3. ($\Rightarrow$) Suppose $o_i \in$ Outcomes($\mathit{jj}\, T_i$) for $i = 1, 2$. Then $\mathit{jj}\, T_i \xRightarrow{\tau}_{w_i} \mu_i$ for some stable μ_i with $o_i = \langle w_i, \text{Success}(\mu_i)\rangle$. By Proposition 2.11(4) we have $\mathit{jj}\, T_1 \,{}_p\!\oplus\, T_2 \xRightarrow{\tau}_w \mu$ with $w = pw_1 + (1-p)w_2$ and $\mu = p\,\mu_1 + (1-p)\,\mu_2$. Clearly, μ is also stable and Success(μ) = p Success(μ_1) + (1 $-$ p) Success(μ_2). Hence, $o \in$ Outcomes($\mathit{jj}\, T_1 \,{}_p\!\oplus\, T_2$).

   ($\Leftarrow$) Suppose $o \in$ Outcomes($\mathit{jj}\, T_1 \,{}_p\!\oplus\, T_2$). Then there is a stable μ such that $\mathit{jj}\, T_1 \,{}_p\!\oplus\, T_2 \xRightarrow{\tau}_w \mu$ and $o = \langle w, \text{Success}(\mu)\rangle$. By Proposition 2.11(3) there are μ_i for $i = 1, 2$, such that $\mathit{jj}\, T_i \xRightarrow{\tau}_{w_i} \mu_i$ and $w = pw_1 + (1-p)w_2$ and $\mu = p\,\mu_1 + (1-p)\,\mu_2$. As μ_1 and μ_2 are stable, we have $\langle w_i, \text{Success}(\mu_i)\rangle \in$ Outcomes($\mathit{jj}\, T_i$). Moreover, $o = p\,\langle w_1, \text{Success}(\mu_1)\rangle + (1-p)\,\langle w_2, \text{Success}(\mu_2)\rangle$.

4. Suppose $\xRightarrow{\tau}_w q\,\mu_1 + (1-q)\,\mu_2$ and $o_i \in$ Outcomes($\mu_i \mathit{jj}\, T_i$). Then there are stable μ_i with $\mu_i \mathit{jj}\, T_i \xRightarrow{\tau}_{w_i} \mu_i$ and $o_i = \langle w_i, \text{Success}(\mu_i)\rangle$. Using Lemma 3.3, we have that $\mathit{jj}\,(\tau_0.T_1 + \tau_0.T_2) \xRightarrow{\tau}_w q\,(\mu_1 \mathit{jj}\,(\tau_0.T_1 + \tau_0.T_2)) + (1-q)\,(\mu_2 \mathit{jj}\,(\tau_0.T_1 + \tau_0.T_2)) \xrightarrow{\tau}_0 q\,\mu_1 \mathit{jj}\, T_1 + (1-q)\,\mu_2 \mathit{jj}\, T_2 \xRightarrow{\tau}_{w'} \mu'$ with $w' = qw_1 + (1-q)w_2$ and $\mu' = q\,\mu_1 + (1-q)\,\mu_2$. Clearly, μ' is stable and Success(μ') = q Success(μ_1) + (1 $-$ q) Success(μ_2). Hence, $q\,o_1 + (1-q)\,o_2 + \langle w, \vec{0}\rangle \in$ Outcomes($\mathit{jj}\, T_1 \,{}_p\!\oplus\, T_2$).

The converse to part (4) of Lemma E.1 also holds, though its proof is much more complicated.

Lemma E.2 If $o \in$ Outcomes($\mathit{jj}\,(\tau_0.T_1 + \tau_0.T_2)$) then there are $q \in [0,1]$, weight w and distributions μ_1, μ_2 such that $\xRightarrow{\tau}_w q\,\mu_1 + (1-q)\,\mu_2$ and $o = q\,o_1 + (1-q)\,o_2 + \langle w, \vec{0}\rangle$ for certain $o_i \in$ Outcomes($\mu_i \mathit{jj}\, T_i$).

Proof. By mimicking the corresponding proof in [DvGHM09].

Proposition E.3 In a bounded wMDP, for every formula $\phi \in L$ there exists a pair (T_ϕ, v_ϕ) with T_ϕ a multi-success test and $v_\phi \in [0,1]$ such that, for any weight r and distribution μ,

(1) If $\langle r, \mu\rangle \models \phi$ then $\exists o \in$ Outcomes($\mu \mathit{jj}\, T_\phi$) : $v_\phi \leq o + \langle r, \vec{0}\rangle$.

(2) If $\exists o \in$ Outcomes($\mu \mathit{jj}\, T_\phi$) : $v_\phi \leq o + \langle r, \vec{0}\rangle$ then there exists some weight $r' \geq r$ such that $\langle r', \mu\rangle \models \phi$.

T_ϕ is called a *characteristic test* of ϕ and v_ϕ its *target value*.

Proof. For any ϕ 2 L we de ne the pair T_ϕ and v_ϕ by structural induction.

Let ϕ = tt. Take T_ϕ := $\omega_0.\mathbf{0}$ for some ω 2 and v_ϕ := $h0, \vec{\omega}\, i$.

Let ϕ = $h\alpha i_v \psi$. By induction, ψ has a characteristic test T_ψ with target value v_ψ. Take T_ϕ := $a_0.T_\psi$ and v_ϕ := v_ψ + $h\, v, \vec{0}\, i$.

Let ϕ = ϕ_1 ^ ϕ_2. Choose -disjoint tests T_1, T_2 for ϕ_1 and ϕ_2, with target values v_1, v_2. Let p 2 $(0,1)$ be chosen arbitrarily. We de ne T_ϕ := $T_{1\,p}$ T_2 and v_ϕ := p v_1 + (1 p) v_2.

Let ϕ = $\phi_{1\,p}$ ϕ_2. Choose -disjoint tests T_1, T_2 for ϕ_1 and ϕ_2 with target values v_1, v_2, and two fresh success actions ω_1, ω_2. Let T_i^0 := $T_{i\,\frac{1}{2}}$ w_i and v_i^0 := $\frac{1}{2}v_i$ + $\frac{1}{2}h0, \vec{\omega_i}\, i$. Note that for i = 1, 2 we have that T_i^0 is also a characteristic test of ϕ_i with target value v_i. We de ne T_ϕ := $\tau_0.T_1^0$ + $\tau_0.T_2^0$ and v_ϕ := p v_1^0 + (1 p) v_2^0.

We now check by induction on ϕ that (1) and (2) above hold.

(1) Let ϕ = tt. For any con guration $hr,$ i, there exists some o 2 Outcomes(jj $\omega_0.\mathbf{0}$) with $h0, \vec{\omega}\, i$ o o + $hr, \vec{0}\, i$, using Lemma E.1(1).

Let ϕ = $h\alpha i_v \psi$. Suppose $hr,$ i j= ϕ. Then there are $w,$ ^{0} with $=^{\alpha})$ $_w$ ^{0} and hr + w $v,$ ^{0} i j= ψ. By induction, there exists o_ψ 2 Outcomes(^{0} jj T_ψ) with v_ψ o_ψ + hr + w $v, \vec{0}\, i$. By Lemma E.1(2), there is some o 2 Outcomes(jj $a_0.T_\psi$) with o = o_ψ + $hw, \vec{0}\, i$. It follows that v_ϕ = v_ψ + $hv, \vec{0}\, i$ o + $hr, \vec{0}\, i$ as required.

Let ϕ = ϕ_1 ^ ϕ_2. Suppose $hr,$ i j= ϕ. Then $hr,$ i j= ϕ_i for i = 1, 2. By induction, there exists o_i 2 Outcomes(jj T_i) with v_i o_i + $hr, \vec{0}\, i$. By Lemma E.1(3), we have o := p v_1 + (1 p) v_2 2 Outcomes(jj T_ϕ), and v_ϕ o + $hr, \vec{0}\, i$.

Let ϕ = $\phi_{1\,p}$ ϕ_2. Suppose $hr,$ i j= ϕ. Then there are $r_1, r_2,$ $_1,$ $_2$ such that $hr,$ i = p $hr_1,$ $_1$ i + (1 p) $hr_2,$ $_2$ i and $hr_i,$ $_i$ i j= ϕ_i for i = 1, 2. By induction,there exists some o_i 2 Outcomes($_i$ jj T_i) with v_i o_i + $hr_i, \vec{0}\, i$. By Lemma E.1(1), we have $h0, \vec{\omega_i}\, i$ 2 Outcomes($_i$ jj ω_i). Since T_i^0 = $T_{i\,\frac{1}{2}}$ ω_i, by Lemma E.1(3), there is some o_i^0 := $\frac{1}{2}$ o_i + $\frac{1}{2}$ $h0, \vec{\omega_i}\, i$ 2 Outcomes($_i$ jj T_i^0). We note that

$$v_i^0 \;:=\; \frac{1}{2}\; v_i + \frac{1}{2}\; h0, \vec{\omega_i}\, i \qquad \frac{1}{2}\; (o_i + hr_i, \vec{0}\, i) + \frac{1}{2}\; h0, \vec{\omega_i}\, i \;=\; o_i^0 + \frac{1}{2}\; hr_i, \vec{0}\, i.$$

By Lemma E.1(4), there exists some o := p o_1^0 + (1 p) o_2^0 2 Outcomes(jj ($\tau_0.T_1^0$ + $\tau_0.T_2^0$)). Therefore,

$$v_\phi \qquad p\;\; (o_1^0 + \frac{1}{2}\; hr_1, \vec{0}\, i) + (1 \quad p)\;\; (o_2^0 + \frac{1}{2}\; hr_2, \vec{0}\, i) \;=\; o + \frac{1}{2}\; hr, \vec{0}\, i \qquad o + hr, \vec{0}\, i.$$

(2) Let ϕ = tt. For any con guration $hr,$ i, we have $hr,$ i j= ϕ.

Let $\phi = h\alpha i_v \psi$. Suppose there exists some o 2 Outcomes($jj\, T_\phi$) with $v_\phi \quad o + hr, \vec{0}\, i$. It is easy to see that o 6= $\vec{0}$ because $o(\omega) \quad v_\phi(\omega)$ 6= 0 for some ω 2 . By Lemma E.1(2) we have $=^a) \ _w \ ^0$ and $o = o^0 + hw, \vec{0}\, i$ for some o^0 2 Outcomes($^0 jj\, T_\psi$). It follows that $v_\psi + hv, \vec{0}\, i \quad o^0 + hw, \vec{0}\, i + hr, \vec{0}\, i$. In other words, $v_\psi \quad o^0 + hr + w \quad v, \vec{0}\, i$. By induction, there is some weight $r^0 \quad r + w \quad v$ with $hr^0, \ ^0 i \models \psi$. Let $r^{00} := \max(0, r^0 \quad w + v)$. Clearly, we have $r^{00} \quad r^0 \quad w + v \quad r$. It holds that $hr^{00}, \ i \models \phi$. To see this, we consider two cases: (i) if $r^{00} = r^0 \quad w + v$ then $r^0 \quad w + v \quad 0$ and by the de nition of $\models$ we get $hr^0 \quad w + v, \ i \models \phi$; (ii) if $r^{00} = 0$ then $r^0 \quad w + v \quad 0$, i.e. $w \quad v \quad r^0$, which implies $hw \quad v, \ ^0 i \models \psi$ by Lemma 3.15 and then $h0, \ i \models \phi$.

Let $\phi = \phi_1 \wedge \phi_2$. Suppose there exists o 2 Outcomes($jj\, T_\phi$) with $v_\phi \quad o + hr, \vec{0}\, i$. By Lemma E.1(3) we have $o = p \ o_1 + (1 \quad p) \ o_2$ for certain o_i 2 Outcomes($jj\, T_i$). Recall that T_1, T_w are -disjoint tests. There exists weight r_i that $v_i \quad o_i + hr_i, \vec{0}\, i$ for both $i = 1, 2$. To see this, we observe that (i) $v_i(\omega) \quad o_i(\omega)$ for all ω 2 for if $v_i(\omega) > o_i(\omega)$ for some i = 1 or 2 then ω must occur in T_i but not in $T_{3 \ i}$, thus $v_{3 \ i}(\omega) = 0$ and $v_\phi(\omega) > o(\omega)$, in contradiction with the assumption; (ii) if x_i and y_i are the weight components of v_i and o_i respectively, then we can simply choose $r_i := \max(0, x_i \quad y_i)$ to ensure that $x_i \quad y_i + r_i$. By induction, there exists some weight $r_i^0 \quad r_i$ such that $hr_i^0, \ i \models \phi_i$, for i = 1 and 2. Let $r^{00} = \max(r_1^0, r_2^0, r)$. By Lemma 3.15 we have $hr^{00}, \ i \models \phi_i$, hence $hr^{00}, \ i \models \phi$.

Let $\phi = \phi_{1\,p} \quad \phi_2$. Suppose there is some o 2 Outcomes($jj\, T_\phi$) such that $v_\phi \quad o + hr, \vec{0}\, i$. By Lemma E.2, there are $q, w, \ _1, \ _2$ such that $=^\tau) \ _w \ q \quad _1 + (1 \quad q) \quad _2$ and $o = q \ o_1^0 + (1 \quad q) \ o_2^0 + hw, \vec{0}\, i$ for certain o_i^0 2 Outcomes($_i jj\, T_i^0$). Now $v_i^0(\omega_i) = o_i^0(\omega_i) = \frac{1}{2}$ for both i = 1 and 2, so using that T_1, T_2 are -disjoint tests, $\frac{1}{2}p = p \ v_1^0(\omega_1) = v_\phi(\omega_1) \quad o(\omega_1) = q \ o_1^0(\omega_1) = \frac{1}{2}q$ and likewise $\frac{1}{2}(1 \quad p) = (1 \quad p) \ v_2^0(\omega_2) = v_\phi(\omega_2) \quad o(\omega_2) = (1 \quad q) \ o_2^0(\omega_2) = \frac{1}{2}(1 \quad q)$. Together, these inequalities say that $p = q$. Exactly as in the previous case one obtains $v_i^0 \quad o_i^0 + hr_i, \vec{0}\, i$ for some weight r_i, where i = 1, 2. Given that $T_i^0 = T_{i\,\frac{1}{2}} \quad w_i$, using Lemma E.1(3), it must be that $o_i^0 = \frac{1}{2}o_i + \frac{1}{2}\vec{\omega_i}$ for some o_i 2 Outcomes($_i jj\, T_i$) with $v_i \quad o_i + 2r_i$. By induction, there exists some $r_i^0 \quad 2r_i$ such that $hr_i^0, \ i \models \phi_i$, for i = 1 and 2. Let $r^{00} = \max(r, \ pr_1^0 + (1 \quad p)r_2^0)$. We have $hr^{00}, \ i \models \phi$, using Lemma 3.15.

Corollary E.4 [Theorem 4.12] In a bounded wMDP, if v^r_{mmay} then there exists some r^0 such that $r^0 \quad r$ and $L(0, \ ) \quad L(r^0, \ )$.

Proof. For any ϕ 2 $L(0, \ )$, we have $h0, \ i \models \phi$. Let T_ϕ be a characteristic test of ϕ with target value v_ϕ. By Proposition E.3(1), there exists some o 2 Outcomes($jj\, T_\phi$) such that $v_\phi \quad o$. Since v^r_{mmay} , there is some o^0 2 Outcomes($jj\, T_\phi$) such that $o \quad o^0 + hr, \vec{0}\, i$. It follows that $v_\phi \quad o_i^0 + hr, \vec{0}\, i$. By Proposition E.3(2), there exists some weight r^0 such that $r^0 \quad r$ and $hr^0, \ i \models \phi$, i.e. ϕ 2 $L(r^0, \ )$.

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