Hitting the nail on the head: Force vectors in verb semantics[1]

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0 Introduction

➢ Theoretical context
- Growing attention for role of forces (force-dynamics) in verbs and prepositions (see star-marked references)
- Forces as vectors (Wolff, Zwarts, Gärdenfors)

➢ Empirical context
- What is the role of force (vectors) in verbs, prepositions, adverbs of contact and impact?
- Verbs like *schlagen* (to hit) and *ziehen* (to pull), prepositions like *an* (on), *auf* (on), *gegen* (against), and adverbs like *hart* (hard) and *leicht* (lightly)
- Typical examples in (1), more about their properties later on

(1) a. Maria schlägt hart auf den Nagel.
Maria hits hard on the nail
b. Peter zieht an der Rübe. (Roßdeutscher & Pross 2015)
Peter pulls on the root
a'. Maria schlägt den Nagel in die Tür.
Maria hits the nail into the door
b'. Peter zieht die Rübe aus der Erde. (Roßdeutscher & Pross 2015)
Peter pulls the root out.of the earth

➢ Structure of talk
- A domain of force verbs
- The (Neo)Davidsonian starting point and some puzzles
- Model-theoretic building blocks for a force-based approach
- Lexical definitions and meaning components
- The compositional semantics
- Answering the initial puzzles

1 A domain of force verbs

➢ What is a 'force verb'?
- A force verb is any verb of which the root can occur in a sentence that describes a situation in which an object A (the force exerter) exerts a physical force (however light) on another object B (the force recipient) without necessarily implying a change in the properties of B, yet while allowing for that change.
- force verbs in our sense: *schlagen* (to hit), *drücken* (to push), *ziehen* (to pull), *reiben* (to rub), *pressen* (to press), *treten* (to kick)

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- not force verbs in our sense: *brechen* (to break), *werfen* (to throw), *schleppen* (to drag) (because they entail a change), *stehen* (stand) (because it doesn't allow change)
- close relation with contact (force typically requires contact and contact typically involves some amount of force)

➢ 'Arguments' of force verbs (illustrated in (2))
- Force exerter (a), expressed by subject in active sentence
- Force recipient (b), expressed by object of verb or preposition (alternation)
- Force instrument (c), expressed by *mit* (with)-PP or in verb (*treten* (to kick), *hämmern* (to hammer))
- Force zone (d), part of force recipient specifically affected by force, expressed by locative (place) PP
- Path, with Ground (e), describing motion of force recipient as a result of force, expressed by directional (path) PP

(2) a. Petra (a) schlägt mit einem Hammer (c) auf den Nagel (b).
Petra (a) hits with a hammer (c) on the nail (b)
b. Petra (a) zieht die Rübe (b) mit ihren Händen (c) am Schopf (d) aus der Erde (e).
Petra (a) pulls the root (b) with her hands (c) on.the tuft (d) out.of the earth (e)

➢ Some lexical distinctions between force verbs
- Aspectual distinctions: whether the force applies continuously (*pressen* – to press) or punctually (*schlagen* – to hit)
- Directional distinctions: whether the force is directed towards the recipient (*drücken* – to push) or away from the recipient (*ziehen* – to pull)
- Intensity distinctions: whether the force is intense (*reiben* – to rub, *hauen* - to bash/hit) or not (*streichen* – to stroke, *tippen* – to tap)
- Configurational distinctions: whether the force comes from one side (*drücken* – to push) or more sides (*kneifen* – to pinch)
- Instrumental distinctions: whether the force is mediated by a particular instrument (*treten* – to kick, *hämmern* – to hammer)

➢ Compositional aspects of force verbs
- Interactions with grammar (alternations, cf. Levin 1993, Rossdeutscher & Pross 2015)
e.g. *auf den Nagel schlagen* (to hit on the nail) vs. *den Nagel auf den Kopf schlagen* (to hit the nail on the head) vs. *den Nagel in die Tür schlagen* (to hit the nail into the door)
- Interactions with adverbs like *hart* (hard) and *leicht* (lightly)
e.g. ?*hart*/✓*leicht berühren* (to touch ?hard/✓lightly) vs. ✓*hart*/?*leicht zerren* (to drag/tug ✓hart/?lightly)
- Interactions with particles and prepositions
e.g. **auf*/✓*an etwas ziehen* (to pull *on/✓on something) vs. **an*/✓*auf etwas drücken* (to push *on/✓on something)

➢ A puzzle: interaction between force modifiability and force result
- The specification of a result (*ein* in (3a)) of the force seems to restrict the possibility of force modification

(3) a. Thomas schlägt das Fenster (*hart/*leicht) ein.
Thomas hits the window (*hard/*lightly) in
Thomas breaks the window (*hard/*lightly).

b. Thomas schlägt (hart/leicht) gegen das Fenster.
Thomas hits (hart/lightly) against the window

➢ Also confirmed in questionnaire study with more examples (see appendix):

- test sentences with force verbs with and without resultative particle/preposition and with force (hard/lightly) or temporal/speed (quickly/slowly) modifier (temporal/speed modifiers were used in order to determine whether all modification is out if a (force) result is specified, or just modification of the force component)
- participants rated sentences on a 4-point Likert scale:
1 – clearly bad, 2 – maybe bad, 3 – maybe good, 4 – clearly good
- results:

	without result (schlagen)	with result (einschlagen)
leicht/hart	79.21% / 52.55%	48.95% / 31.16%
langsam/schnell	62.43% / 62.80%	76.35% / 81.36%

Table 1: Percentages of ratings 3 (maybe good) and 4 (clearly good) for all test sentences

- sentences without a resultative particle or preposition and a force modifier were judged significantly better than sentences with a resultative particle or preposition and a force modifier (odds: 4.9, p = .02 for *leicht*; 8.1, p < .01 for *hart*)
- sentences with a resultative particle or preposition and a temporal/speed modifier were judged significantly better than sentences with a resultative particle or preposition and a force modifier (odds: 4.05, p = .03 for *langsam* vs *leicht*; 7, p < .01 for *schnell* vs *leicht*; and 15.7, p < .001 for *langsam* vs *hart*, 27.25, p < .001 for *schnell* vs *hart*)

2 The (Neo)Davidsonian starting point and beyond

➢ The sentences in (4) might have the (Neo)Davidsonian logical forms in (5)

(4) a. Maria schlägt (hart) auf den Nagel.
Maria hits (hard) on the nail
b. Maria schlägt den Nagel (*hart) in die Tür.
Maria hits the nail (*hart) into the door

(5) a. ∃*e* [**schlagen**(*e*) & **agent**(*e*)=**maria** & **hart**(*e*) & **auf**(*e*,**den-nagel**)]
b. ∃*e* [**schlagen**(*e*) & **agent**(*e*)=**maria** & **patient**(*e*,**den-nagel**) & **in**(*e*,**die-tür**)]

➢ A number of puzzles

A There is an entailment from (4b) to (4a) (because in order to move the nail into the door Maria must hit it) but not from (4a) to (4b) (because Maria could hit the nail without it moving). At the moment this is not accounted for by the logical forms in (5ab). What could explain this entailment pattern?
B What is the relation between *auf* in (4a) and the patient role in (4b)?
C How can we account for the fact that *schlagen* (to hit) goes with *auf* (on) and not with *an* (on) (and that *ziehen* (to pull) is the other way around)?
D In what sense can an event be *auf den Nagel* (on the nail) or *in die Tür* (into the door)? How can we distinguish the contributions that these PPs make?
E What does it mean for an event to be *hart* (hard)?
F What is it about *schlagen* (to hit) that it allows modification by *hart* (hard) (as opposed to e.g. *lachen* – to laugh)?
G Why does *hart* (hard) seem to be less acceptable in (4b), where a result is specified?

➢ Our proposal: Considering *the (force) paths* of events (see (6) and (7))
- The internal properties of events are accessed through the paths they describe in real or conceptual space, e.g. Gärdenfors (2000).
- A path is constituted by a trace of force vectors representing the force that the agent exerts on the patient at each point of time during the event (Wolff 2007).
- We assume a general notion of path, in which a path is also present in a stationary situation (e.g. Talmy 2000).
- Resultative sentences involve a representation with two events for caused results (Parsons 1990, Pustejovsky 1991).

(6) a. Maria schlägt (hart) auf den Nagel.
Maria hits (hard) on the nail
b. Maria schlägt den Nagel (*hart) in die Tür.
Maria hits the nail (*hart) into the door

(7) a. $\exists e.\exists p_1$ [SCHLAGEN(e) & PATH(e)=p_1 & AGENT(e)=**maria** & AUF(p_1,**der-nagel**) & HART(p_1)]
b. $\exists e.\exists e_1.\exists e_2.\exists p_2$ [e=e_1+e_2 & CAUSE(e_1,e_2) & SCHLAGEN(e_1) & AGENT(e_1)=**maria** & PATIENT(e_1)=THEME(e_2)=**der-nagel** & PATH(e_2)=p_2 & IN(p_2,**die-tür**)]
(Small caps used for constants that are either primitives or fully definable in terms of primitives.)

3 Model-theoretic building blocks for a force-based approach

➢ Forces
- There is a full set of located force vectors that have an (i) origin, (ii) magnitude, and (iii) direction. This set includes zero vectors. Each set of force vectors with the same spatial origin constitutes a vector space, with the appropriate properties.
- We access space exclusively through located force vectors. A zero force vector is equivalent with an 'old-fashioned' point in space; a non-zero force vector f can be used to represent a force with magnitude $|f|$ working at point ORIGIN(f)=0f.

➢ Objects and space
- With a part-whole structure (e.g. foot part of body)
- For every (material) object x, there is a set SPACE(x) of spatial points that represents the *eigenspace* of x with a proper subset BOUNDARY(x) of boundary points and INTERIOR(x) (the complement of the boundary wrt the eigenspace).

➢ Paths
- A path is a continuous function from a time interval $[t_0,t_1]$ to the set of located force vectors.
- Roughly speaking, a path is a sequence of positions at which forces might be exerted.
- $p(t)$ is the force vector f representing the force exerted at time t.
- A path p may be constant, i.e. map every t of its domain to the same vector f.
- A *force path* is a path that includes *non-zero* force vectors in its range.

➢ Events in time and space
- Some mereological structure, to allow sums (+) of events
- For every event e, there is the interval TIME(e) that represents the running time of e.
- For any event e, PATH(e) is the path that corresponds to e, if defined.

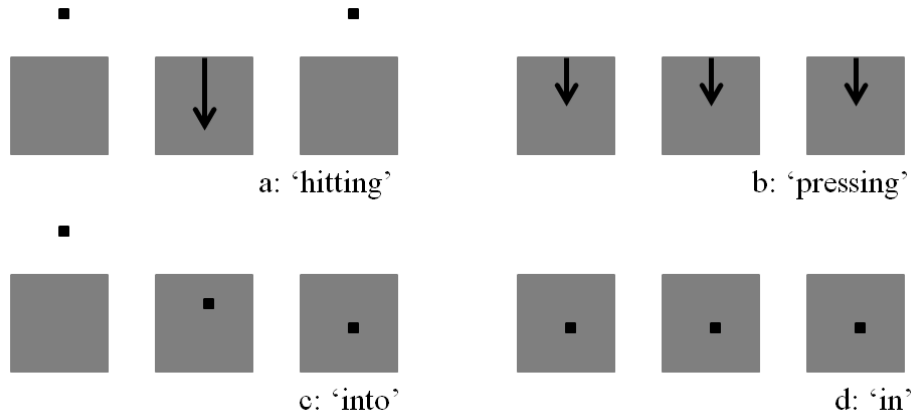

Figure 1: Subsequent 'snapshots' $p(t_0)$, $p(t_i)$, $p(t_1)$ from different paths

➢ Participants of events
- If PATH(e) is a force path, then there is a participant AGENT(e) that is the exerter of the forces and a participant PATIENT(e) that is the recipient of the forces. Every non-zero force vector of the path must be located on the boundary of the eigenspace of PATIENT(e).
- If PATH(e) is a force path, then INSTRUMENT(e) is that part of AGENT(e) that is in contact with PATIENT(e).
- For any event e with PATH(e), there is a participant THEME(e) that occupies subsequent positions of PATH(e) along the running time of e.

➢ Causation (based on Wolff 2007)
- CAUSE(e_1,e_2): if PATH(e_1)(t_i) + TENDENCY(e_1)(t_i) is collinear with PATH(e_2) while TENDENCY(e_1)(t_i) is not.
- Roughly, CAUSE(e_1,e_2) if the forces that the agent of e_1 exerts on the patient of e_1 (i.e. PATH(e_1)) + the other forces working on the patient, i.e. TENDENCY(e_1)) lead to forces that point in the same direction as the patient's motion in e_2 (i.e. PATH(e_2)), while TENDENCY(e_1) does not point in the same direction as PATH(e_1) and PATH(e_2).

(8) Maria schlägt den Nagel in die Wand.

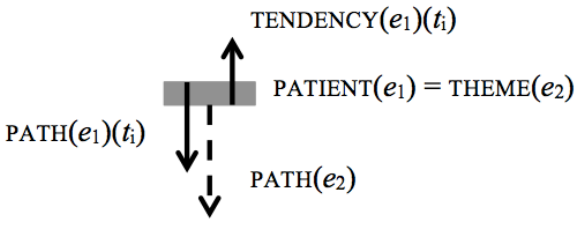

Figure 2: Force interaction in CAUSE(e_1,e_2) at moment t_i

4 Lexical definitions and meaning components

➢ Aspectual components
- PUNCTUAL(p) iff $\exists! t$ [$|p(t)| > 0$]
- CONTINUOUS(p) iff $\forall t$ [$|p(t)| > 0$]

➢ Directional components

- MOVING(p) iff for $\forall t.\forall t'$ [$t \neq t' \rightarrow$ ORIGIN($p(t)$) $\neq$ ORIGIN($p(t')$)][2]
- INTR(p,x) iff $\exists t.\exists$s [ORIGIN($p(t)$) $\in$ BOUNDARY(x) & s > 0 & END(s$p(t)$) $\in$ INTERIOR(x)]
- EXTR(p,x) iff $\exists t.\forall$s [ORIGIN($p(t)$) $\in$ BOUNDARY(x) & s > 0 & END(s$p(t)$) $\notin$ SPACE(x)]

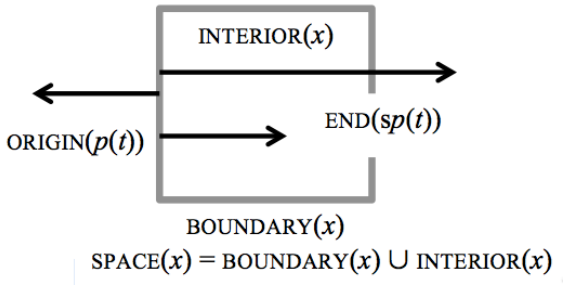

Figure 3: INTR(p,x) and EXTR(p,x)

➢ Some force verbs

- SCHLAGEN = $\lambda e.\exists p$ [p=PATH(e) & PUNCTUAL(p) & INTR(p,PATIENT(e))] - (hit)
- DRÜCKEN = $\lambda e.\exists p$ [p=PATH(e) & CONTINUOUS(p) & INTR(p,PATIENT(e))] - (push)
- REIBEN = $\lambda e.\exists p$ [p=PATH(e) & CONTINUOUS(p) & INTR(p,PATIENT(e)) & MOVING(p)] - (rub)
- ZIEHEN = $\lambda e.\exists p$ [p=PATH(e) & CONTINOUS(p) & EXTR(p,PATIENT(e))] - (pull)

➢ Some prepositions

- AUF(x) = λp [INTR(p,x)] - (on)
- GEGEN(x) = λp [INTR(p,x)][3] - (against)
- AN(x) = λp [EXTR(p,x)] - (on)
- IN(x) = λp [$p(t_1) \in$ INTERIOR(x)][4] - (in)
- ÜBER(x) = λp [INTR(p,x) & MOVING(p)] - (over)

➢ Two force adverbs

- HART = $\lambda p.\exists t$ [$|p(t)| >$ M_C], where M_C is some average force magnitude for comparison - (hard)
- LEICHT = $\lambda p.\forall t$ [$|p(t)| <$ M_C], where M_C is some average force magnitude for comparison - (lightly)

5 The compositional semantics

➢ Type-shift functions

- Mapping set of paths to modifier of events
  $\lambda P.\lambda E.\lambda e.\exists p$ [PATH(e)=p & $P(p)$ & $E(e)$]
- Mapping set of paths to complex predicate constructor
  $\lambda P.\lambda E.\lambda x.\lambda e.\exists e_1.\exists e_2.\exists p$ [e=e_1+e_2 & CAUSE(e_1,e_2) & $E(e_1)$ & PATIENT(e_1)=THEME(e_2)=x & PATH(e_2)=p & $P(p)$]
- Kratzer's (1996) way of introducing the external argument

[2] This is a single move. For e.g. rubbing repeatedly over the same spot we need pluralization at some level.
[3] For practical purposes *auf* (on) and *gegen* (against) receive the same analysis here, despite their different uses.
[4] This definition might not account for all occurrences of *in* (in), e.g. *in das Kissen schlagen* 'hit into the pillow', where the force path does not have to end up in the interior of the pillow.

➢ *Maria schlägt hart auf den Nagel*
Maria hits hard on the nail

1 schlagen = λe [SCHLAGEN(e)]
2 auf = $\lambda x.\lambda p$ [AUF(p,x)]
3 auf den Nagel = λp [AUF(p,**den-nagel**)] $\Rightarrow$ $\lambda E.\lambda e.\exists p$ [PATH(e)=p & AUF(p,**den-nagel**) & E(e)]
4 auf den Nagel schlagen = $\lambda e.\exists p$ [PATH(e)=p & AUF(p,**den-nagel**) & SCHLAGEN(e)]
5 hart = λp [HART(p)] $\Rightarrow$ $\lambda E.\lambda e.\exists p$ [PATH(e)=p & HART(p) & E(e)]
6 hart auf den Nagel schlagen = $\lambda e.\exists p$ [PATH(e)=p & HART(p) & AUF(p,**den-nagel**) & SCHLAGEN(e)]
7 Maria schlägt hart auf den Nagel = $\exists e.\exists p$ [PATH(e)=p & HART(p) & AUF(p,**den-nagel**) & SCHLAGEN(e) & AGENT(e) = MARIA]

➢ *Maria schlägt den Nagel in die Tür*
Maria hits the nail into the door

1 schlagen = λe [SCHLAGEN(e)]
2 in = $\lambda x.\lambda p$ [IN(p,x)]
3 in die Tür = λp [IN(p,**die-tür**)] $\Rightarrow$ $\lambda E.\lambda x.\lambda e.\exists e_1.\exists e_2.\exists p$ [e=e_1+e_2 & CAUSE(e_1,e_2) & E(e_1) & PATIENT(e_1)=THEME(e_2)=x & PATH(e_2)=p & IN(p,**die-tür**)]
4 in die Tür schlagen = $\lambda x.\lambda e.\exists e_1.\exists e_2.\exists p$ [e=e_1+e_2 & CAUSE(e_1,e_2) & SCHLAGEN(e_1) & PATIENT(e_1)=THEME(e_2)=x & PATH(e_2)=p & IN(p,**die-tür**)]
5 den Nagel in die Tür schlagen = $\lambda e.\exists e_1.\exists e_2.\exists p$ [e=e_1+e_2 & CAUSE(e_1,e_2) & SCHLAGEN(e_1) & PATIENT(e_1)=THEME(e_2)=**den-nagel** & PATH(e_2)=p & IN(p,**die-tür**)]
6 Maria schlägt den Nagel in die Tür = $\exists e.\exists e_1.\exists e_2.\exists p$ [e=e_1+e_2 & CAUSE(e_1,e_2) & SCHLAGEN(e_1) & PATIENT(e_1)=THEME(e_2)=**den-nagel** & PATH(e_2)=p & IN(p,**die-tür**) & AGENT(e_1) = MARIA]

6 Solving the puzzles

A There is an entailment from (4b) to (4a) (because in order to move the nail into the door Maria must hit it) but not from (4a) to (4b) (because Maria could hit the nail without it moving). At the moment not accounted for by the logical forms in (5ab). What could explain this entailment pattern?
$\exists e.\exists e_1.\exists e_2.\exists p$ [e=e_1+e_2 & CAUSE(e_1,e_2) & SCHLAGEN(e_1) & PATIENT(e_1)=THEME(e_2)=**den-nagel** & PATH(e_2)=p & IN(p,**die-tür**) & AGENT(e) = MARIA]
$\Rightarrow$ $\exists e_1$ [SCHLAGEN(e_1) & PATIENT(e_1)=**den-nagel** & AGENT(e) = MARIA]
$\Rightarrow$ $\exists e_1.\exists p$ [PATH(e_1)=p & SCHLAGEN(e_1) & PATIENT(e_1)=**den-nagel** & AGENT(e) = MARIA & INTR(p,PATIENT(e_1))]

B What is the relation between *auf* (on) in (4a) and the patient role in (4b)?
In both cases, force vectors are located on the boundary of the object: the argument of *auf* and the patient of the event. (The argument of *auf* is always a patient.)

C How can we account for the fact that *schlagen* (to hit) goes with *auf* (on) and not with *an* (on) (and that *ziehen* (to pull) is the other way around)?
Both *schlagen* and *auf* are characterized by internally directed force vectors, while *an* and *ziehen* are both characterized by externally directed force vectors.

D In what sense can an event be *auf den Nagel* (on the nail) or *in die Tür* (into the door)? How can we distinguish the contributions that these PPs make?
Only in the sense that those PPs apply to the *paths* corresponding to those events. *Auf den Nagel* specifies a force path and *in die Tür* specifies a path of motion.

E What does it mean for an event to be *hart* (hard)?
This means that a force vector associated to the event is above a certain magnitude.

F What is it about *schlagen* (to hit) that it allows modification by *hart* (hard) (as opposed to e.g. *lachen* – to laugh)?
Schlagen is one verb from a class of verbs that is associated to a force path. *Lachen* is not associated to a force path.

G Why does *hart* (hard) seem to be less acceptable in (4b), where a result is specified?
CAUSE requires an operation of vector addition of the force (vector) exerted by the agent on the patient at the moment of contact between the two entities. Once this computation has happened, the original force vectors of PATH(e_1) become unavailable for modification by any adverb that requires a force vector with a magnitude (bigger than zero).[5]

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[5] Modifiers allowed in this complex predicate construction (like *schief* (diagonally), *gerade* (straight); *schnell* (quickly), *langsam* (slowly); *vorsichtig* (carefully), *hektisch* (hastily)) either modify the PP (PATH(e_2)), i.e. apply to the path of the second event, modify the complex event (e=e_1+e_2), or be licensed by the subject/agent of the event (AGENT(e_1)).

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Appendix: Some example sentences from the questionnaires

- Julia drückt hart gegen die Tür.
  'Julia pushes hard against the door.'
- Maike drückt die Pappe nach dem Kleben schnell an.
  'Maike presses the cardboard quickly together after gluing it.'
- Sandra drückt die Seite vom Karton langsam ein.
  'Sandra pushes the sides of the cardboard box towards each other.'
- Chris drückt die Tür hart zu.
  'Chris closes the door hard (while pushing it).'
- Tobias schlägt das Fenster leicht ein.
  'Tobias breaks the window lightly.'
- Alex schlägt schnell auf den Nagel.
  'Alex quickly hits the nail.'
- Alex schlägt den Nagel langsam in die Wand.
  'Alex hits the nail slowly into the wall.'
- Tobias zieht leicht an der Tür.
  'Tobias pulls lightly on the door.'
- Andrea zieht langsam an Florians Arm.
  'Andrea pulls slowly on Florian's arm.'
- Maike zieht die Wurzeln hart aus der Erde.
  'Maike pulls the roots hard out of the earth.'
- Jan zieht die Tür leicht zu.
  'Jan closes the door lightly (while pulling it).'