Reflections on, and predictions for, support systems for the development of programs

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ASE 2008-09-19

Instead of conventional “Thank you for invite”

Huge Thank you!

My first time at an ASE:
see real conversation between different approaches!

Contents

Me + FM support tools

- contributed to transition from VDL to VDM (language description)
  - we wrote large (including PL/I) definitions with minimal tooling
  - experience: problems mainly hit us when changes made!
  - originated much of "VDM" as for program development
- used support systems since Jim King's "Effigy"
  - I worry they lock user in to one method
  - suspect they constrain thought
  - (but used Effigy for top-down design!)
- "Formal Development Support System" IBM Hursley (1970s)
  - it was so rigid, even I couldn't use it!
- more public is the mural system (below) Manchester (1980s)
- observed use of many TP systems
  - have seen people "hack" without understanding *what* they are proving
- Rodin Toolset (below)

mural [JJLM91]

- order of proof steps was very flexible
- a “logical frame” (e.g. used for LPF)
- focus on building theories
- but only minimal automatic support
- best seen as a UI experiment
- built from VDM spec
- implemented in SmallTalk’80 (turned out to be a mistake)
- kept multiple proof attempts — difficult to delete!
- book now on the web
- yes, it contains the VDM spec (evolved)

Rodin ToolSet

- (EU) project developed tools “Rodin ToolSet”
- open source - available from SourceForge
- kernel + plugins
- Eclipse based
- one key advantage: background proving
- also: nice work on computing impact of changes (minimise re-proof)
- now being used in the (EU) DEPLOY IP project
- “road map” discusses plans; invites input
- tool engenders an approach: everything in Contexts/Machines

Contents

1. Background
2. Arguments
3. An example: ACMs
   - Where to start – a specification
   - Splitting atoms (gently) in abstract state
   - Retaining less history
   - The four-slot representation
   - Conclusions
4. Overall conclusions/summary

Claim: (software) design is hard

- (Yes, I know this is stating the obvious!)
- requires a strange mixture of important (big) insights and detailed symbol pushing
- layers of *abstraction* (backed up by formal rules) are all we've got!
- (for many reasons) we must take our own medicine
    - reluctance to so do: Effigy, . . .
- we must be seen to take our own medicine

Belief: there is a long way to go

- no current "formal methods support system" gives software engineers anything like the support given to hardware designers by their CAD systems
- destruction of design history is intellectual vandalism
- current programming languages are ill-suited to documenting design
- have to stop trying to build "complete" support systems
- build/link components
- care! there are pitfalls here (e.g. different logics)
- "whole" system includes (IMHO) tracking all versions
- . . . and all tests on all versions

Thesis: level of generality

- there are all sorts of things I'd like to prove
- mistake to fix on one method (example below)
- but want more than a general purpose TP system
- there is no point in proving all of the verification conditions for one version of a program and then running a different (buggy) version — so systems have to control all versions, tests, verifications, changes etc.
- might call it a "method frame"
- this can present problems diagnostics (and performance)

My hope for AI contribution

- (discussions with Ireland/Bundy)
- they planning to “mine proofs”
- loses info on how created (order) — cf. mural view
- info on failed attempts long discarded!
- at detailed level, can’t trace what “copied” from where
- system learns high-level strategy (not tactics?)

Argument: don't get locked into "legacy code" corner

- (I'm aware there are a lot of "testing" folk at ASE)
- BTW: I started out in IBM's Product Test division
- ideas like "abstract interpretation" ("symbolic execution"): making real progress for non-trivial systems
- handling "legacy" systems presents another set of challenges — here the aim is to accumulate information such as avoidance of certain sorts of bad behaviour; again, such hard won information should not be discarded
- even if can't work on "green fields" projects, look at rational reconstructions

Theses

- model checking not only needs “abstraction” but it should be equipped to use ones that are available from design
- there are enough common problems between the various sorts of tool that interfacing components is imperative — apart from simple syntactic interfaces
- . . . much in the style of the EPFL paper (Beyer?) Wednesday morning (“predicate abstraction” + “explicit analysis”)
- such integration can pose hard semantic challenges

Idea: direct support for SOS

was almost subject of ASE conf paper (now [HJ08])

- do not have complete axiom systems for any widely used programming language (by a big margin)
- might therefore have to reason from, say, an operational semantics
- our paper builds on mural approach
- obviously use Floyd/Hoare-like rules is applicable
- in fact, would be nice if this system supports justification of such rules

Broader worries: industrial perspective

- getting the “right” specification [JHJ07] for a non-trivial system is at least as much an issue as showing that a design matches its specification
- even during design, everything will change (in fact, designing for flexibility is often more important than aiming for efficiency) — systems must maximise what is preserved over such changes
- we have to build our tools so that they can interface with whatever in-house engineering systems are being used by organisations we expect to adopt our formal tools
- . . .

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Key abstractions

Argument: flexibility on methods

- Pre/post-conditions (as in VDM/B/. . .)
    - design by *sequential* “operation decomposition rules”
    - Floyd/Hoare-like rules (coping with relational post-conditions)
- Rely/Guarantee “thinking”
    - not (just) a specific set of rules
    - show importance of “frames” (cf. Separation Logic)
    - using “auxiliary variables”
- Abstract objects
    - choice of abstract data objects key for specifications
    - data “reification” (classic-VDM / Nipkow’s rule)
    - link with R/G development
- “fiction of atomicity”
    - “splitting (software) atoms safely” [Jon07]
    - cf. database transactions [JLRW05], . . .
    - cf. POBL [Jon96]

While (operation decomposition) rule

$$\boxed{While\text{-}I}\ \frac{\begin{array}{l} S\ \textbf{sat}\ (P \land b, P \land W) \\ P \ \Rightarrow\ \delta_l(b) \end{array}}{mk\text{-}While(b, S)\ \textbf{sat}\ (P, P \land \neg\, b \land W^*)}$$

There's no reason why a system should hardwire the (standard) Hoare rule the rules should be data (to a method frame)

"posit and prove" is one way of supporting design;
"Verified by Construction" has been shown to be viable for large systems

One R/G rule

$$\boxed{Par\text{-}I}\ \frac{\begin{array}{l}\{P, R \vee Gr\} \vdash sl \ \textbf{sat}\ (Gl, Ql) \\ \{P, R \vee Gl\} \vdash sr \ \textbf{sat}\ (Gr, Qr) \\ Gl \vee Gr \ \Rightarrow\ G \\ \overleftharpoon{P} \wedge Ql \wedge Qr \wedge (R \vee Gl \vee Gr)^* \ \Rightarrow\ Q\end{array}}{\{P, R\} \vdash mk\text{-}Par(sl, sr)\ \textbf{sat}\ (G, Q)}$$

. . . and there are lots more where this one came from

Subtle link between R/G and data reification

cf. [Jon07]

- in $FINDP$
    - we have $t \leftarrow min(t, local)$ in n parallel processes
    - assuming we don't want to "lock" t
    - need a representation that preserves R/G conditions
    - simple to represent as t as $min(et, ot)$
- SIEVE
    - we have to remove an element from a set s
    - assuming we don't want to "lock" s (big!)
    - need a representation that preserves R/G conditions $s \subseteq \overleftarrow{s}$
    - (less obvious) represent s as a bit vector
- Simpson
    - extremely interesting
    - my claim: this is the essence of Simpson's contribution

ACMs: [JP08]

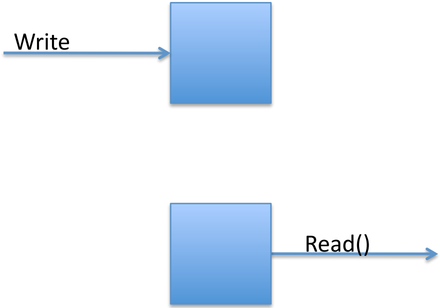
Communication (Atomic?)

Write(42)

x := Read()

ACMs

Atomic and (trying for) Asynchronous



Simpson's algorithm

- Simpson's algorithm
- several other folk still working on this
- run through my "rational reconstruction"
    - "explanation" via layers of abstraction
- essential to get the big steps right before detailed proof
- apologies for so much argument about eight lines of code . . .

formulae in small fount not meant to be read!

Specification

$$
\begin{aligned}
\Sigma^a \;::\;\; & data\text{-}w\colon Value^* \\
& fresh\text{-}w\colon \mathbb{N} \\
& hold\text{-}r\colon \mathbb{N}
\end{aligned}
$$

$$
\begin{aligned}
&\textbf{inv}\ (mk\text{-}\Sigma^a(data\text{-}w, fresh\text{-}w, hold\text{-}r)) \triangleq \\
&\qquad\qquad fresh\text{-}w, hold\text{-}r \in \{1..\textbf{len}\ data\text{-}w\} \wedge hold\text{-}r \leq fresh\text{-}w
\end{aligned}
$$

$$\sigma_0^a = mk\text{-}\Sigma^a([\mathtt{x}], 1, 1)$$

```
while true do
    $start\text{-}Write(v\colon Value)\colon data\text{-}w \leftarrow data\text{-}w \curvearrowright [v]$;
    $commit\text{-}Write()\colon fresh\text{-}w \leftarrow$ len $data\text{-}w$
  od
while true do
    $start\text{-}Read()\colon hold\text{-}r \leftarrow fresh\text{-}w$;
    $end\text{-}Read()r\colon Value\colon r \leftarrow data\text{-}w(i)$ for some $i \in \{hold\text{-}r..fresh\text{-}w\}$
  od
```

Example 3

$$\begin{array}{lcl}
\mathit{start\text{-}Read}() & .. & \mathit{mk}\text{-}\Sigma^a([\mathrm{x}], 1, 1) \\
\mathit{start\text{-}Write}(\mathtt{y}) & .. & \mathit{mk}\text{-}\Sigma^a([\mathrm{x}, \mathrm{y}], 1, 1) \\
\mathit{commit\text{-}Write}() & .. & \mathit{mk}\text{-}\Sigma^a([\mathrm{x}, \mathrm{y}], 2, 1) \\
\mathit{start\text{-}Write}(\mathtt{z}) & .. & \mathit{mk}\text{-}\Sigma^a([\mathrm{x}, \mathrm{y}, \mathrm{z}], 2, 1) \\
\mathit{commit\text{-}Write}() & .. & \mathit{mk}\text{-}\Sigma^a([\mathrm{x}, \mathrm{y}, \mathrm{z}], 3, 1) \\
\mathit{end\text{-}Read}() & .. & r \in \{\mathtt{x}, \mathtt{y}, \mathtt{z}\} \\
\mathit{start\text{-}Read}() & .. & \mathit{mk}\text{-}\Sigma^a([\mathrm{x}, \mathrm{y}, \mathrm{z}], 3, 3) \\
\mathit{end\text{-}Read}() & .. & r = \mathtt{z}
\end{array}$$

Specification in terms of four sub-operations ($Write$)

Atomic operations — therefore pure pre/post specification

```
while true do
    $start\text{-}Write(v\colon Value)\colon data\text{-}w \leftarrow data\text{-}w \curvearrowright [v];$
    $commit\text{-}Write()\colon fresh\text{-}w \leftarrow \textbf{len}\ data\text{-}w$
  od
||
⋮
```

```
$Write(v\colon Value)$
  $start\text{-}Write(v\colon Value)$
    wr $data\text{-}w$
    post $data\text{-}w = \overleftarrow{data\text{-}w} \curvearrowright [v]$
  $commit\text{-}Write(v\colon Value)$
    rd $data\text{-}w$
    wr $fresh\text{-}w$
    pre $data\text{-}w(\textbf{len}\ data\text{-}w) = v$
    post $fresh\text{-}w = \textbf{len}\ data\text{-}w$
```

Specification in terms of four sub-operations ($Read$)

```
$\vdots$
$||$
while true do
        $start\text{-}Read()\colon hold\text{-}r \leftarrow fresh\text{-}w;$
        $end\text{-}Read()r\colon Value\colon r \leftarrow data\text{-}w(i)$ for some $i \in \{hold\text{-}r..fresh\text{-}w\}$
    od
```

```
$Read()r\colon Value$
    local $hold\text{-}r\colon \mathbb{N}$
    $start\text{-}Read()$
        wr $hold\text{-}r$
        rd $fresh\text{-}w$
        post $hold\text{-}r = fresh\text{-}w$
    $end\text{-}Read()r\colon Value$
        rd $data\text{-}w, fresh\text{-}w$
        post $\exists i \in \{hold\text{-}r..fresh\text{-}w\} \cdot r = data\text{-}w(i)$
```

General messages

- note “algorithmic” specification
- “fiction of atomicity”
  - but single “atomic” variable does not cover all behaviour
- “frames” (for rd/wr access)
  - plus “local”
- data abstraction

Splitting atoms in Σ^a (Write)

Accept overlap (only read/write) — therefore rely/guarantee

$\mathit{Write}(v\colon \mathit{Value})$

  $\mathit{start\text{-}Write}(v\colon \mathit{Value})$

    rd $\mathit{fresh\text{-}w}$

    wr $\mathit{data\text{-}w}$

    rely $\mathit{fresh\text{-}w} = \overleftarrow{\mathit{fresh\text{-}w}} \wedge \mathit{data\text{-}w} = \overleftarrow{\mathit{data\text{-}w}}$

    guar $\{1..\mathit{fresh\text{-}w}\} \lhd \mathit{data\text{-}w} = \{1..\mathit{fresh\text{-}w}\} \lhd \overleftarrow{\mathit{data\text{-}w}}$

    post $\mathit{data\text{-}w} = \overleftarrow{\mathit{data\text{-}w}} \curvearrowright [v]$

  $\mathit{commit\text{-}Write}(v\colon \mathit{Value})$

    rd $\mathit{data\text{-}w}$

    wr $\mathit{fresh\text{-}w}$

    pre $\mathit{data\text{-}w}(\mathbf{len}\ \mathit{data\text{-}w}) = v$

    rely $\mathit{fresh\text{-}w} = \overleftarrow{\mathit{fresh\text{-}w}} \wedge \mathit{data\text{-}w} = \overleftarrow{\mathit{data\text{-}w}}$

    post $\mathit{fresh\text{-}w} = \mathbf{len}\ \mathit{data\text{-}w}$

Splitting atoms in Σ^a $(Read)$

$Read()r\colon Value$
$\quad start\text{-}Read()$
$\qquad$ **rd** $fresh\text{-}w$
$\qquad$ **wr** $hold\text{-}r$
$\qquad$ **rely** $hold\text{-}r = \overleftarrow{hold\text{-}r}$
$\qquad$ **post** $hold\text{-}r \in \{\overleftarrow{fresh\text{-}w}, fresh\text{-}w\}$
$\quad end\text{-}Read()r\colon Value$
$\qquad$ **rd** $data\text{-}w, fresh\text{-}w, hold\text{-}r$
$\qquad$ **rely** $hold\text{-}r = \overleftarrow{hold\text{-}r} \wedge \forall i \in \{hold\text{-}r .. \overleftarrow{fresh\text{-}w}\} \cdot data\text{-}w(i) = \overleftarrow{data\text{-}w}(i)$
$\qquad$ **post** $\exists i \in \{hold\text{-}r .. \overleftarrow{fresh\text{-}w}\} \cdot r = \overleftarrow{data\text{-}w}(i)$

General messages

- phasing
  - makes clear $start\text{-}Write$ cannot interfere with $commit\text{-}Write$
  - avoids implications in rely conditions
- frames plus phasing significantly simplify R/G assertions
- cf. $rely\text{-}start\text{-}Write$ on Σ^a above

Retaining less history

A data reification exercise — still very general

$$\begin{aligned}\Sigma^i \;::\;& \mathit{data\text{-}w}\colon X \xrightarrow{m} \mathit{Value}\\ & \mathit{fresh\text{-}w}\colon X\\ & \mathit{hold\text{-}r}\colon X\\ & \mathit{hold\text{-}w}\colon X\end{aligned}$$

$$\sigma_0^i = \mathit{mk}\text{-}\Sigma^i(\{\alpha \mapsto \mathtt{x}\}, \alpha, \alpha, \alpha)$$

Relating Σ^i to Σ^a

Using Nipkow's rule

$$r(\sigma_1^a, \sigma_1^i) \wedge post^i(\sigma_1^i, \sigma_2^i) \;\Rightarrow\; \exists \sigma_2^a \in \Sigma^a \cdot post^a(\sigma_1^a, \sigma_2^a) \wedge r(\sigma_2^a, \sigma_2^i)$$

$$r : \Sigma^a \times \Sigma^i \to \mathbb{B}$$

$$\begin{array}{l} r(mk\text{-}\Sigma^a(data\text{-}w^a, fresh\text{-}w^a, hold\text{-}r^a), \\ \qquad\qquad mk\text{-}\Sigma^i(data\text{-}w^i, fresh\text{-}w^i, hold\text{-}r^i, hold\text{-}w^i)) \quad \triangleq \\ \quad \textbf{rng}\; data\text{-}w^i \subseteq \textbf{elems}\; data\text{-}w^a \wedge \\ \quad data\text{-}w^a(fresh\text{-}w^a) = data\text{-}w^i(fresh\text{-}w^i) \wedge \\ \quad data\text{-}w^a(hold\text{-}r^a) = data\text{-}w^i(hold\text{-}r^i) \end{array}$$

Specifications of the sub-operations on Σ^i

Still overlapped — still rely/guarantee

```
$Write(v\colon Value)$
  **local** $hold\text{-}w\colon X$
  $start\text{-}Write(v\colon Value)$
    **rd** $hold\text{-}r, fresh\text{-}w$
    **wr** $data\text{-}w, hold\text{-}w$
    **rely** $fresh\text{-}w = \overleftarrow{fresh\text{-}w} \wedge data\text{-}w = \overleftarrow{data\text{-}w}$
    **guar** $\{\overleftarrow{hold\text{-}r}, hold\text{-}r\} \lhd data\text{-}w = \{\overleftarrow{hold\text{-}r}, hold\text{-}r\} \lhd \overleftarrow{data\text{-}w}$
    **post** $hold\text{-}w \in (X - \{fresh\text{-}w, \overleftarrow{hold\text{-}r}, hold\text{-}r\}) \wedge data\text{-}w = \overleftarrow{data\text{-}w} \dagger \{hold\text{-}w \mapsto v\}$
  $commit\text{-}Write(v\colon Value)$
    **rd** $data\text{-}w, hold\text{-}w$
    **wr** $fresh\text{-}w$
    **pre** $data\text{-}w(hold\text{-}w) = v$
    **rely** $fresh\text{-}w = \overleftarrow{fresh\text{-}w} \wedge data\text{-}w = \overleftarrow{data\text{-}w}$
    **post** $fresh\text{-}w = hold\text{-}w$
```

Specifications of the sub-operations on Σ^i

```
$Read()r\colon Value$
  $start\text{-}Read()$
    **rd** $fresh\text{-}w$
    **wr** $hold\text{-}r$
    **rely** $hold\text{-}r = \overleftarrow{hold\text{-}r}$
    **post** $hold\text{-}r \in \{\overleftarrow{fresh\text{-}w}, fresh\text{-}w\}$
  $end\text{-}Read()r\colon Value$
    **rd** $hold\text{-}r, data\text{-}w$
    **rely** $hold\text{-}r = \overleftarrow{hold\text{-}r} \wedge data\text{-}w(hold\text{-}r) = \overleftarrow{data\text{-}w}(hold\text{-}r)$
    **post** $r = data\text{-}w(hold\text{-}r)$
```

General messages

- simpler R/G because of read/write frames
- data reification
  - (potentially) reducing non-determinism
  - use of VDM's other reification rule
- still have "bold" atomicity assumptions
  - couldn't update $data\text{-}w$ atomically on any reasonable machine
- still work to be done
- role of data reification in achieving rely conditions
- Simpson's representation crucial

The four-slot representation

Focus on Simpson's inspiration

$$\begin{array}{lll}
\Sigma^r & :: & \mathit{data\text{-}w}\colon P \times S \xrightarrow{m} \mathit{Value} \\
 & & \mathit{pair\text{-}w}\colon P \\
 & & \mathit{pair\text{-}r}\colon P \\
 & & \mathit{slot\text{-}w}\colon P \xrightarrow{m} S \\
 & & \mathit{wp\text{-}w}\colon P \\
 & & \mathit{ws\text{-}w}\colon S \\
 & & \mathit{rs\text{-}r}\colon S
\end{array}$$

where (key assumptions about granularity (ρ)):

$P, S = \mathit{Token}$-**set**

$P = S$
card $P = 2$
$\rho(i) \neq i$

Specifications of the sub-operations on Σ^r

```
$Write(v\colon Value)$
  local $wp\text{-}w\colon P$
  local $ws\text{-}w\colon S$
  $start\text{-}Write(v\colon Value)$
    rd $pair\text{-}r, slot\text{-}w$
    wr $data\text{-}w$
    rely $slot\text{-}w = \overleftarrow{slot\text{-}w} \wedge data\text{-}w = \overleftarrow{data\text{-}w}$
    guar $\{(\overleftarrow{pair\text{-}r}, slot\text{-}w(\overleftarrow{pair\text{-}r})), (pair\text{-}r, slot\text{-}w(pair\text{-}r))\} \lhd data\text{-}w =$
            $\{(\overleftarrow{pair\text{-}r}, slot\text{-}w(\overleftarrow{pair\text{-}r})), (pair\text{-}r, slot\text{-}w(pair\text{-}r))\} \lhd \overleftarrow{data\text{-}w}$
    post $wp\text{-}w = \rho(\overleftarrow{pair\text{-}r}) \wedge ws\text{-}w = \rho(slot\text{-}w(wp\text{-}w)) \wedge data\text{-}w(wp\text{-}w, ws\text{-}w) = v$
  $commit\text{-}Write()$
    wr $pair\text{-}w, slot\text{-}w$
    rely $pair\text{-}w = \overleftarrow{pair\text{-}w} \wedge slot\text{-}w = \overleftarrow{slot\text{-}w}$
    guar $slot\text{-}w(pair\text{-}r) = \overleftarrow{slot\text{-}w}(pair\text{-}r)$
    post $slot\text{-}w(wp\text{-}w) = ws\text{-}w \wedge pair\text{-}w = wp\text{-}w$
```

Satisfies guarantee conditions (as well as post)

```
$Write(v: Value)$
  local $wp\text{-}w: P$
  local $ws\text{-}w: S$
    $wp\text{-}w \leftarrow \rho(pair\text{-}r)$;
    $ws\text{-}w \leftarrow \rho(slot\text{-}w(wp\text{-}w))$;
    $data\text{-}w(wp\text{-}w, ws\text{-}w) \leftarrow v$;
    $slot\text{-}w(wp\text{-}w) \leftarrow ws\text{-}w$;
    $pair\text{-}w \leftarrow wp\text{-}w$

$Read()r: Value$
  local $rs\text{-}r: S$
    $pair\text{-}r \leftarrow pair\text{-}w$;
    $rs\text{-}r \leftarrow slot\text{-}w(pair\text{-}r)$;
    $r \leftarrow data\text{-}w(pair\text{-}r, rs\text{-}r)$
```

Conclusions (on example)

- all at ASE probably accept “refinement from abstractions”
- “splitting atoms” – a new/old formal addition
- subsidiary points
  - rely/guarantee “thinking”
  - remember frame descriptions
  - combination with data reification
  - link with “phasing”
  - “auxiliary variables” + Nipkow’s rule
  - tool support
  - try to avoid “coding logic into values”
- these ideas are not (all) in any single “method”

Contents

(My) general conclusions

- OK, tools *do* matter
- no one method solves covers all problems
- must design interworking components
  - XML is not the answer!
  - generality: diagnostics via rules?
  - . . . performance via abstract interpretation?
- I hope to explore "method frame"
  - flexibility
  - way to combine
- GUI does matter
  - view onto huge data structure
  - much of which generated
  - quick/easy check to avoid wasting time trying to prove non-theorems?
- Programming Languages — part of the problem (not solution)
  - "must try harder"
  - old TOPD question

Personal preferences

- (post this meeting) I still plan to work on Verification!
- a couple more examples
  - I got into “formal methods” (1969) because of PL/I-F compiler mess
  - my attempts to prove extant programs always *failed*
  - concede: I didn’t have the good tools available here at ASE 2008
  - but: finding errors late still leaves “scrap and rework” issue
- real message: continue to search for synergy
  - I happen to be on Verification side of the fence
  - I do see the payoff with model checking etc.
  - Confess: VxC suites my personal research tastes!
- . . . and I hope to work with AI people!

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Plug!

ASE community might also like
VSTTE (because the “E” is for “experiments”)
Toronto, October 6^{th}–9^{th}

http://qpq.csl.sri.com/vsr/vstte-08