JOURNAL OF FORMALIZED MATHEMATICS
Volume 2, Released 1990, Published 2003
Inst. of Computer Science, Univ. of Białystok

The Limit of a Composition of Real Functions

Jarosław Kotowicz
Warsaw University
Białystok

Summary. The theorem on the proper and improper limit of a composition of real functions at a point, at infinity and one-side limits at a point are presented.

MML Identifier: LIMFUNC4.

WWW: http://mizar.org/JFM/Vol2/limfunc4.html

The articles [9], [10], [2], [3], [8], [11], [1], [7], [5], [6], and [4] provide the notation and terminology for this paper.

We adopt the following convention: r, r_1, r_2, g, g_1, g_2, x_0 denote real numbers and f_1, f_2 denote partial functions from $\mathbb{R}$ to $\mathbb{R}$.

We now state a number of propositions:

(1) Let s be a sequence of real numbers and X be a set. Suppose $\operatorname{rng} s \subseteq \operatorname{dom}(f_2 \cdot f_1) \cap X$. Then $\operatorname{rng} s \subseteq \operatorname{dom}(f_2 \cdot f_1)$ and $\operatorname{rng} s \subseteq X$ and $\operatorname{rng} s \subseteq \operatorname{dom} f_1$ and $\operatorname{rng} s \subseteq \operatorname{dom} f_1 \cap X$ and $\operatorname{rng}(f_1 \cdot s) \subseteq \operatorname{dom} f_2$.

(2) Let s be a sequence of real numbers and X be a set. If $\operatorname{rng} s \subseteq \operatorname{dom}(f_2 \cdot f_1) \setminus X$, then $\operatorname{rng} s \subseteq \operatorname{dom}(f_2 \cdot f_1)$ and $\operatorname{rng} s \subseteq \operatorname{dom} f_1$ and $\operatorname{rng} s \subseteq \operatorname{dom} f_1 \setminus X$ and $\operatorname{rng}(f_1 \cdot s) \subseteq \operatorname{dom} f_2$.

(3) Suppose that

(i) f_1 is divergent in $+\infty$ to $+\infty$,

(ii) f_2 is divergent in $+\infty$ to $+\infty$, and

(iii) for every r there exists g such that $r < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $+\infty$.

(4) Suppose that

(i) f_1 is divergent in $+\infty$ to $+\infty$,

(ii) f_2 is divergent in $+\infty$ to $-\infty$, and

(iii) for every r there exists g such that $r < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $-\infty$.

(5) Suppose that

(i) f_1 is divergent in $+\infty$ to $-\infty$,

(ii) f_2 is divergent in $-\infty$ to $+\infty$, and

(iii) for every r there exists g such that $r < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $+\infty$.

(6) Suppose that

(i) f_1 is divergent in $+\infty$ to $-\infty$,

(ii) f_2 is divergent in $-\infty$ to $-\infty$, and

(iii) for every r there exists g such that $r < g$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $-\infty$.

(7) Suppose that

(i) f_1 is divergent in $-\infty$ to $+\infty$,

(ii) f_2 is divergent in $+\infty$ to $+\infty$, and

(iii) for every r there exists g such that $g < r$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $+\infty$.

(8) Suppose that

(i) f_1 is divergent in $-\infty$ to $+\infty$,

(ii) f_2 is divergent in $+\infty$ to $-\infty$, and

(iii) for every r there exists g such that $g < r$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $-\infty$.

(9) Suppose that

(i) f_1 is divergent in $-\infty$ to $-\infty$,

(ii) f_2 is divergent in $-\infty$ to $+\infty$, and

(iii) for every r there exists g such that $g < r$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $+\infty$.

(10) Suppose that

(i) f_1 is divergent in $-\infty$ to $-\infty$,

(ii) f_2 is divergent in $-\infty$ to $-\infty$, and

(iii) for every r there exists g such that $g < r$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $-\infty$.

(11) Suppose that

(i) f_1 is left divergent to $+\infty$ in x_0,

(ii) f_2 is divergent in $+\infty$ to $+\infty$, and

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is left divergent to $+\infty$ in x_0.

(12) Suppose that

(i) f_1 is left divergent to $+\infty$ in x_0,

(ii) f_2 is divergent in $+\infty$ to $-\infty$, and

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is left divergent to $-\infty$ in x_0.

(13) Suppose that

(i) f_1 is left divergent to $-\infty$ in x_0,

(ii) f_2 is divergent in $-\infty$ to $+\infty$, and

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \text{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is left divergent to $+\infty$ in x_0.

(14) Suppose that

(i) f_1 is left divergent to $-\infty$ in x_0,

(ii) f_2 is divergent in $-\infty$ to $-\infty$, and

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is left divergent to $-\infty$ in x_0.

(15) Suppose that

(i) f_1 is right divergent to $+\infty$ in x_0,

(ii) f_2 is divergent in $+\infty$ to $+\infty$, and

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is right divergent to $+\infty$ in x_0.

(16) Suppose that

(i) f_1 is right divergent to $+\infty$ in x_0,

(ii) f_2 is divergent in $+\infty$ to $-\infty$, and

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is right divergent to $-\infty$ in x_0.

(17) Suppose that

(i) f_1 is right divergent to $-\infty$ in x_0,

(ii) f_2 is divergent in $-\infty$ to $+\infty$, and

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is right divergent to $+\infty$ in x_0.

(18) Suppose that

(i) f_1 is right divergent to $-\infty$ in x_0,

(ii) f_2 is divergent in $-\infty$ to $-\infty$, and

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is right divergent to $-\infty$ in x_0.

(19) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is left divergent to $+\infty$ in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0 - g, x_0[$ holds $f_1(r) < \lim_{x_0^-} f_1$.

Then $f_2 \cdot f_1$ is left divergent to $+\infty$ in x_0.

(20) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is left divergent to $-\infty$ in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0 - g, x_0[$ holds $f_1(r) < \lim_{x_0^-} f_1$.

Then $f_2 \cdot f_1$ is left divergent to $-\infty$ in x_0.

(21) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is right divergent to $+\infty$ in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0 - g, x_0[$ holds $\lim_{x_0^-} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is left divergent to $+\infty$ in x_0.

(22) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is right divergent to $-\infty$ in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0 - g, x_0[$ holds $\lim_{x_0^-} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is left divergent to $-\infty$ in x_0.

(23) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is right divergent to $+\infty$ in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0, x_0 + g[$ holds $\lim_{x_0^+} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is right divergent to $+\infty$ in x_0.

(24) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is right divergent to $-\infty$ in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0, x_0 + g[$ holds $\lim_{x_0^+} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is right divergent to $-\infty$ in x_0.

(25) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is left divergent to $+\infty$ in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0, x_0 + g[$ holds $f_1(r) < \lim_{x_0^+} f_1$.

Then $f_2 \cdot f_1$ is right divergent to $+\infty$ in x_0.

(26) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is left divergent to $-\infty$ in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0, x_0 + g[$ holds $f_1(r) < \lim_{x_0^+} f_1$.

Then $f_2 \cdot f_1$ is right divergent to $-\infty$ in x_0.

(27) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is left divergent to $+\infty$ in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $f_1(g) < \lim_{+\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $+\infty$.

(28) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is left divergent to $-\infty$ in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $f_1(g) < \lim_{+\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $-\infty$.

(29) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is right divergent to $+\infty$ in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $\lim_{+\infty} f_1 < f_1(g)$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $+\infty$.

(30) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is right divergent to $-\infty$ in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $\lim_{+\infty} f_1 < f_1(g)$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $-\infty$.

(31) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is left divergent to $+\infty$ in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $f_1(g) < \lim_{-\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $+\infty$.

(32) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is left divergent to $-\infty$ in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $f_1(g) < \lim_{-\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $-\infty$.

(33) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is right divergent to $+\infty$ in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $\lim_{-\infty} f_1 < f_1(g)$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $+\infty$.

(34) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is right divergent to $-\infty$ in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $\lim_{-\infty} f_1 < f_1(g)$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $-\infty$.

(35) Suppose that

(i) f_1 is divergent to $+\infty$ in x_0,

(ii) f_2 is divergent in $+\infty$ to $+\infty$, and

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent to $+\infty$ in x_0.

(36) Suppose that

(i) f_1 is divergent to $+\infty$ in x_0,

(ii) f_2 is divergent in $+\infty$ to $-\infty$, and

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent to $-\infty$ in x_0.

(37) Suppose that

(i) f_1 is divergent to $-\infty$ in x_0,

(ii) f_2 is divergent in $-\infty$ to $+\infty$, and

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent to $+\infty$ in x_0.

(38) Suppose that

(i) f_1 is divergent to $-\infty$ in x_0,

(ii) f_2 is divergent in $-\infty$ to $-\infty$, and

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is divergent to $-\infty$ in x_0.

(39) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is divergent to $+\infty$ in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) \neq \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is divergent to $+\infty$ in x_0.

(40) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is divergent to $-\infty$ in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) \neq \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is divergent to $-\infty$ in x_0.

(41) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is right divergent to $+\infty$ in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) > \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is divergent to $+\infty$ in x_0.

(42) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is right divergent to $-\infty$ in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) > \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is divergent to $-\infty$ in x_0.

(43) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is divergent to $+\infty$ in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0, x_0 + g[$ holds $f_1(r) \neq \lim_{x_0^+} f_1$.

Then $f_2 \cdot f_1$ is right divergent to $+\infty$ in x_0.

(44) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is divergent to $-\infty$ in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0, x_0 + g[$ holds $f_1(r) \neq \lim_{x_0^+} f_1$.

Then $f_2 \cdot f_1$ is right divergent to $-\infty$ in x_0.

(45) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is divergent to $+\infty$ in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $f_1(g) \neq \lim_{+\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $+\infty$.

(46) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is divergent to $-\infty$ in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $f_1(g) \neq \lim_{+\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $+\infty$ to $-\infty$.

(47) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is divergent to $+\infty$ in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $f_1(g) \neq \lim_{-\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $+\infty$.

(48) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is divergent to $-\infty$ in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $f_1(g) \neq \lim_{-\infty} f_1$.

Then $f_2 \cdot f_1$ is divergent in $-\infty$ to $-\infty$.

(49) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is left divergent to $+\infty$ in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) < \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is divergent to $+\infty$ in x_0.

(50) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is left divergent to $-\infty$ in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) < \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is divergent to $-\infty$ in x_0.

(51) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is divergent to $+\infty$ in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0 - g, x_0[$ holds $f_1(r) \neq \lim_{x_0^-} f_1$.

Then $f_2 \cdot f_1$ is left divergent to $+\infty$ in x_0.

(52) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is divergent to $-\infty$ in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \operatorname{dom} f_1 \cap]x_0 - g, x_0[$ holds $f_1(r) \neq \lim_{x_0^-} f_1$.

Then $f_2 \cdot f_1$ is left divergent to $-\infty$ in x_0.

(53) Suppose that

(i) f_1 is divergent in $+\infty$ to $+\infty$,

(ii) f_2 is convergent in $+\infty$, and

(iii) for every r there exists g such that $r < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is convergent in $+\infty$ and $\lim_{+\infty}(f_2 \cdot f_1) = \lim_{+\infty} f_2$.

(54) Suppose that

(i) f_1 is divergent in $+\infty$ to $-\infty$,

(ii) f_2 is convergent in $-\infty$, and

(iii) for every r there exists g such that $r < g$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is convergent in $+\infty$ and $\lim_{+\infty}(f_2 \cdot f_1) = \lim_{-\infty} f_2$.

(55) Suppose that

(i) f_1 is divergent in $-\infty$ to $+\infty$,

(ii) f_2 is convergent in $+\infty$, and

(iii) for every r there exists g such that $g < r$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is convergent in $-\infty$ and $\lim_{-\infty}(f_2 \cdot f_1) = \lim_{+\infty} f_2$.

(56) Suppose that

(i) f_1 is divergent in $-\infty$ to $-\infty$,

(ii) f_2 is convergent in $-\infty$, and

(iii) for every r there exists g such that $g < r$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is convergent in $-\infty$ and $\lim_{-\infty}(f_2 \cdot f_1) = \lim_{-\infty} f_2$.

(57) Suppose that

(i) f_1 is left divergent to $+\infty$ in x_0,

(ii) f_2 is convergent in $+\infty$, and

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is left convergent in x_0 and $\lim_{x_0^-}(f_2 \cdot f_1) = \lim_{+\infty} f_2$.

(58) Suppose that

(i) f_1 is left divergent to $-\infty$ in x_0,

(ii) f_2 is convergent in $-\infty$, and

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \operatorname{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is left convergent in x_0 and $\lim_{x_0^-}(f_2 \cdot f_1) = \lim_{-\infty} f_2$.

(59) Suppose that

(i) f_1 is right divergent to $+\infty$ in x_0,

(ii) f_2 is convergent in $+\infty$, and

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is right convergent in x_0 and $\lim_{x_0+}(f_2 \cdot f_1) = \lim_{+\infty} f_2$.

(60) Suppose that

(i) f_1 is right divergent to $-\infty$ in x_0,

(ii) f_2 is convergent in $-\infty$, and

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is right convergent in x_0 and $\lim_{x_0+}(f_2 \cdot f_1) = \lim_{-\infty} f_2$.

(61) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is left convergent in $\lim_{x_0-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0 - g, x_0[$ holds $f_1(r) < \lim_{x_0-} f_1$.

Then $f_2 \cdot f_1$ is left convergent in x_0 and $\lim_{x_0-}(f_2 \cdot f_1) = \lim_{\lim_{x_0-} f_1 -} f_2$.

(62) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is right convergent in $\lim_{x_0+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0, x_0 + g[$ holds $\lim_{x_0+} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is right convergent in x_0 and $\lim_{x_0+}(f_2 \cdot f_1) = \lim_{\lim_{x_0+} f_1 +} f_2$.

(63) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is right convergent in $\lim_{x_0-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0 - g, x_0[$ holds $\lim_{x_0-} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is left convergent in x_0 and $\lim_{x_0-}(f_2 \cdot f_1) = \lim_{\lim_{x_0-} f_1 +} f_2$.

(64) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is left convergent in $\lim_{x_0+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0, x_0 + g[$ holds $f_1(r) < \lim_{x_0+} f_1$.

Then $f_2 \cdot f_1$ is right convergent in x_0 and $\lim_{x_0+}(f_2 \cdot f_1) = \lim_{\lim_{x_0+} f_1 -} f_2$.

(65) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is left convergent in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $f_1(g) < \lim_{+\infty} f_1$.

Then $f_2 \cdot f_1$ is convergent in $+\infty$ and $\lim_{+\infty}(f_2 \cdot f_1) = \lim_{\lim_{+\infty} f_1^-} f_2$.

(66) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is right convergent in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $\lim_{+\infty} f_1 < f_1(g)$.

Then $f_2 \cdot f_1$ is convergent in $+\infty$ and $\lim_{+\infty}(f_2 \cdot f_1) = \lim_{\lim_{+\infty} f_1^+} f_2$.

(67) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is left convergent in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $f_1(g) < \lim_{-\infty} f_1$.

Then $f_2 \cdot f_1$ is convergent in $-\infty$ and $\lim_{-\infty}(f_2 \cdot f_1) = \lim_{\lim_{-\infty} f_1^-} f_2$.

(68) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is right convergent in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $\lim_{-\infty} f_1 < f_1(g)$.

Then $f_2 \cdot f_1$ is convergent in $-\infty$ and $\lim_{-\infty}(f_2 \cdot f_1) = \lim_{\lim_{-\infty} f_1^+} f_2$.

(69) Suppose that

(i) f_1 is divergent to $+\infty$ in x_0,

(ii) f_2 is convergent in $+\infty$, and

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is convergent in x_0 and $\lim_{x_0}(f_2 \cdot f_1) = \lim_{+\infty} f_2$.

(70) Suppose that

(i) f_1 is divergent to $-\infty$ in x_0,

(ii) f_2 is convergent in $-\infty$, and

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$.

Then $f_2 \cdot f_1$ is convergent in x_0 and $\lim_{x_0}(f_2 \cdot f_1) = \lim_{-\infty} f_2$.

(71) Suppose that

(i) f_1 is convergent in $+\infty$,

(ii) f_2 is convergent in $\lim_{+\infty} f_1$,

(iii) for every r there exists g such that $r < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]r, +\infty[$ holds $f_1(g) \neq \lim_{+\infty} f_1$.

Then $f_2 \cdot f_1$ is convergent in $+\infty$ and $\lim_{+\infty}(f_2 \cdot f_1) = \lim_{\lim_{+\infty} f_1} f_2$.

(72) Suppose that

(i) f_1 is convergent in $-\infty$,

(ii) f_2 is convergent in $\lim_{-\infty} f_1$,

(iii) for every r there exists g such that $g < r$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists r such that for every g such that $g \in \mathrm{dom}\, f_1 \cap]-\infty, r[$ holds $f_1(g) \neq \lim_{-\infty} f_1$.

Then $f_2 \cdot f_1$ is convergent in $-\infty$ and $\lim_{-\infty}(f_2 \cdot f_1) = \lim_{\lim_{-\infty} f_1} f_2$.

(73) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is left convergent in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) < \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is convergent in x_0 and $\lim_{x_0}(f_2 \cdot f_1) = \lim_{\lim_{x_0} f_1^-} f_2$.

(74) Suppose that

(i) f_1 is left convergent in x_0,

(ii) f_2 is convergent in $\lim_{x_0^-} f_1$,

(iii) for every r such that $r < x_0$ there exists g such that $r < g$ and $g < x_0$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0 - g, x_0[$ holds $f_1(r) \neq \lim_{x_0^-} f_1$.

Then $f_2 \cdot f_1$ is left convergent in x_0 and $\lim_{x_0^-}(f_2 \cdot f_1) = \lim_{\lim_{x_0^-} f_1} f_2$.

(75) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is right convergent in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $\lim_{x_0} f_1 < f_1(r)$.

Then $f_2 \cdot f_1$ is convergent in x_0 and $\lim_{x_0}(f_2 \cdot f_1) = \lim_{\lim_{x_0} f_1^+} f_2$.

(76) Suppose that

(i) f_1 is right convergent in x_0,

(ii) f_2 is convergent in $\lim_{x_0^+} f_1$,

(iii) for every r such that $x_0 < r$ there exists g such that $g < r$ and $x_0 < g$ and $g \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap]x_0, x_0 + g[$ holds $f_1(r) \neq \lim_{x_0^+} f_1$.

Then $f_2 \cdot f_1$ is right convergent in x_0 and $\lim_{x_0^+}(f_2 \cdot f_1) = \lim_{\lim_{x_0^+} f_1} f_2$.

(77) Suppose that

(i) f_1 is convergent in x_0,

(ii) f_2 is convergent in $\lim_{x_0} f_1$,

(iii) for all r_1, r_2 such that $r_1 < x_0$ and $x_0 < r_2$ there exist g_1, g_2 such that $r_1 < g_1$ and $g_1 < x_0$ and $g_1 \in \mathrm{dom}(f_2 \cdot f_1)$ and $g_2 < r_2$ and $x_0 < g_2$ and $g_2 \in \mathrm{dom}(f_2 \cdot f_1)$, and

(iv) there exists g such that $0 < g$ and for every r such that $r \in \mathrm{dom}\, f_1 \cap (]x_0 - g, x_0[\cup]x_0, x_0 + g[)$ holds $f_1(r) \neq \lim_{x_0} f_1$.

Then $f_2 \cdot f_1$ is convergent in x_0 and $\lim_{x_0}(f_2 \cdot f_1) = \lim_{\lim_{x_0} f_1} f_2$.

REFERENCES

[1] Czesław Byliński. Partial functions. *Journal of Formalized Mathematics*, 1, 1989. http://mizar.org/JFM/Vol1/partfun1.html.

[2] Krzysztof Hryniewiecki. Basic properties of real numbers. *Journal of Formalized Mathematics*, 1, 1989. http://mizar.org/JFM/Vol1/real_1.html.

[3] Jarosław Kotowicz. Real sequences and basic operations on them. *Journal of Formalized Mathematics*, 1, 1989. http://mizar.org/JFM/Vol1/seq_1.html.

[4] Jarosław Kotowicz. The limit of a real function at a point. *Journal of Formalized Mathematics*, 2, 1990. http://mizar.org/JFM/Vol2/limfunc3.html.

[5] Jarosław Kotowicz. The limit of a real function at infinity. *Journal of Formalized Mathematics*, 2, 1990. http://mizar.org/JFM/Vol2/limfunc1.html.

[6] Jarosław Kotowicz. The one-side limits of a real function at a point. *Journal of Formalized Mathematics*, 2, 1990. http://mizar.org/JFM/Vol2/limfunc2.html.

[7] Jarosław Kotowicz. Properties of real functions. *Journal of Formalized Mathematics*, 2, 1990. http://mizar.org/JFM/Vol2/rfunct_2.html.

[8] Konrad Raczkowski and Paweł Sadowski. Topological properties of subsets in real numbers. *Journal of Formalized Mathematics*, 2, 1990. http://mizar.org/JFM/Vol2/rcomp_1.html.

[9] Andrzej Trybulec. Tarski Grothendieck set theory. *Journal of Formalized Mathematics*, Axiomatics, 1989. http://mizar.org/JFM/Axiomatics/tarski.html.

[10] Andrzej Trybulec. Subsets of real numbers. *Journal of Formalized Mathematics*, Addenda, 2003. http://mizar.org/JFM/Addenda/numbers.html.

[11] Edmund Woronowicz. Relations defined on sets. *Journal of Formalized Mathematics*, 1, 1989. http://mizar.org/JFM/Vol1/relset_1.html.

Received September 5, 1990

Published January 2, 2004